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# Design of an end effector exchange device for a light assembly robot /

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# DESIGN OF AN END EFFECTOR EXCHANGE DEVICE FOR A LIGHT ASSEMBLY ROBOT

BY

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**ABSTRACT:**

This thesis project focused on designing a prototype device to allow a light assembly robot to exchange end effectors. The design criteria for the coupling, included a need for a simple mechanical positive fail safe locking mechanism. Also, pneumatic and electrical needs were established through research into the state of the art in end effector design today.

A prototype was constructed and tested. The testing revealed several problems. First, a completely rigid base for the decoupling mechanism is essential. Second, a robot with high precision and repeatability specifications is required. Barring these two specifications, the device still functioned 80% of the time during testing.

The remainder of the project presents conceptual ideas for a production design. An injection molded plastic part is suggested rather than the machined aluminum prototype.

# CHAPTER 1

## SURVEY OF THE STATE OF THE ART IN ROBOT END EFFECTORS

### INTRODUCTION

New technology in recent years has led to new developments in end effector design.

A robot end effector can be defined as "any device which attaches to the wrist of a robot enabling it to perform a specified task." [1] End effectors are used for gripping objects, welding, spray coating, processing, and many other specialized tasks. They can be classified in terms of their function and design. Robot applications typically necessitate sensory feedback for adaptive control as in robotic arc welding. The following chapter is a summary of recent advances in end effector design as well as an informative guide to the use of sensors in direct relation to the end effector.

The subject can be broken into two major areas: end effectors and sensors. The first subject area includes four subcategories of end effectors: grippers, welding end effectors, spray coating, and end effectors for processing operations. The second subject is divided into two parts: arc welding sensors and sensors other than those used for arc welding.

SECTION I--END EFFECTORS

I. GRIPPERS

A gripper is defined as an end effector capable of grasping an object in some manner. Grippers fall into three categories [2]:

1. Mechanical finger type
2. Vacuum and magnetic type
3. Specialized type

1. MECHANICAL FINGER GRIPPERS

These grippers can be further classified by number of fingers, external vs. internal grasping (see Fig. 1), and single vs. double grippers (see Fig. 2). In addition, the type of mechanical actuation serves as a final distinction. Grippers can be translational (parallel) or pivotal (swinging). They are actuated in a variety of ways including linkage, gear and rack, cam, screw, and wire and pulley. They are powered primarily by pneumatic, hydraulic, or servo electric means. Commercial grippers typically are double fingered, pneumatically actuated, and incorporate a spring return or two way motion on the fingers. At the present time, industry specially designs grippers for operations unfit for a simple grasping action. Some more common special designs feature the use of expanding concentric cylinders or cones to grip circular objects internally (see Fig. 3), the use of adjustable jaws to grip irregular objects, tendon actuated fingers providing a lighter and smaller hand, and three-fingered designs permitting anthropomorphic motions such as twisting a screwdriver or assembling an electronic circuit board [3].

## 2. VACUUM AND MAGNETIC GRIPPERS

VACUUM--These grippers are used primarily for smooth flat surfaces of non-ferrous materials (see Fig. 4). Commercial systems utilize suction cups in a single or multiple array. Vacuum is supplied naturally by negative pressure created as air is expelled from beneath the cup, or alternately, a vacuum pump can supply the necessary suction to the cup [4]

MAGNETIC--Electromagnets are used in conjunction with a robot-controlled power source to facilitate easy workpiece separation for this gripper. Various arrangements allow grasping of ferrous materials (see Fig. 5 for example of dual electromagnetic gripper). Permanent magnets and stripping devices are employed in designs where the robot handles less fragile workpieces [5].

## 3. SPECIALIZED GRIPPERS

Since robots are applied in many areas requiring more than just grasping a simple object, the need has arisen for special end effectors catering to more specific gripping needs. Industry typically purchases these grippers on a one-of-a-kind basis. The following is a summary of such grippers.

INFLATABLE--Based on expanding diaphragm, bags, or tubes, these end effectors function by gripping the inside of hollow objects or by enveloping the whole object, inflating and thus securing it to the robot. Other schemes use liquid or powder filled containers to conform to a workpart. Inflatable fingers made of polyurethane with serrations on the non-gripping side grasp parts by curling around them when the fingers are inflated [4].

UNIQUE--Hooks are used to transport hot parts and containers. Ladles are used in metal working processes. Fabric handling of sheets of material has proven successful by lifting with adhesive strips and opposing racks of pins on a sliding mount (see Fig. 6) [6]. Research in picking randomly oriented (but similar) parts from a bin has led to three approaches: two using suction cups in both single and multiple configurations, and one with a parallel motion gripper. The single cup is mounted on a compliant stem which adapts to the surface and senses contact; the multiple cup model senses contour points with its stems and adapts to the surface. The parallel jaw arrangement senses overload and reorients the wrist accordingly [7]. Applications using new visual sensors (mentioned later) are addressing the problem of retrieving (and orienting) parts that are randomly oriented.

## II. WELDING END EFFECTORS

Robotic welding is twofold: Arc welding and spot welding. Both use conventional welding methods but are applied and positioned by the robot. This really is where the problems arise; good positioning and control of the weld bead are accomplished through sensory feedback (discussed in Section 2). Welding end effectors include:

1. Arc welding end effectors
2. Spot welding end effectors

### 1. ARC WELDING END EFFECTORS

Robotic arc welding involves the use of a wire feed mechanism in conjunction with a torch mounted on the robot wrist (see Fig. 7) [5]. Robotic welding systems are single pass or multipass. Single pass systems perform sensory operations simultaneously with welding operations. Multipass systems first calculate the weld path by passing sensors over the weld area and follow the remaining passes with weld beads. The welding gun is a modified standard, semi-automatic gun fitted to the robot wrist. Some are water cooled, and most designs incorporate a method to remove spatter from the nozzle. Three common methods are pulsing air through the nozzle, periodically scraping the nozzle by means of a built-in sliding scraper, and moving the tip to a wire brush or reamer. The welding consumable (varies depending on material application) is pushed through the nozzle at a controlled rate. In addition, the current or voltage is also regulated by the robot [8]. Commercial robotic welders primarily use a procedure which involves preparing a set of voltage values and wire feed rates for a given application; the robot selects these during the program.

2. SPOT WELDING END EFFECTORS

Robotic spot welding has been proven commercially since the mid-seventies in the automotive industry. The spot welding gun, like the arc welding torch, is really a standard gun modified to fit on a robot wrist (see Fig. 8). The system is capable of applying welds to flat, simple curved, and compound curved surfaces. [1]

## III. SPRAY COATING END EFFECTORS

Spray coating is defined as applying a substance to a workpiece by spraying. Spray painting and undercoating automobiles is a good example. In robotic spray coating, the spray nozzle is the end effector. The setup usually incorporates a color/material changing system capable of clearing the pipe and nozzle before switching to the new desired color/material. The spray coating end effector itself is not a complicated unit (see Fig. 9); again, it is the control that presents the problems. A robot is usually taught to mimic a human operator's motions through the use of either a small "teaching arm" or by moving the robot arm manually and recording the motion in the program [9].

## IV. END EFFECTORS FOR OTHER OPERATIONS

Operations other than welding and spray coating are called processing operations [5]. These are summarized below:

INSERT ATTACHMENTS--Special tooling on the wrist allows for parts insertion such as springs into a valve head assembly in the automotive industry.

STUD WELDING HEAD--A modified stud welding head is fed studs through a tube to automate this tool.

HEAT TORCH--These are directly mounted to the wrist and are used in foundry operations.

PNEUMATIC TOOLS--Examples include wrist mounted nutrunners, screwdrivers, and impact wrenches.

GLUE GUNS--Application of adhesives is simple with wrist mounted gun.

ROUTERS, SANDERS, AND GRINDERS--Wrist mounted belt grinders, disk grinders (see Fig. 10), wire brushes, routers, etc., used in a tool mode; alternatively, robots can present the workpiece to the stationary tool [10].

DRILLS--The aerospace industry has really latched on to robotic drilling and hence advanced the art. Conventional drills can be wrist mounted, or a locking bushing can be utilized with a self-feed drill. This mechanism allows the robot to position the self-guided drill, disengage while the hole is drilled, and picked up the next self-feed drill. Laser drilling is on the threshold of becoming commercially available. Carbon dioxide lasers have yet to reach required power but may prove useful in the future [11]. The primary advantage to laser drilling over conventional means is elimination of dull bits and the problems of sharpening.

## SECTION 2--SENSORS

This section treats welding and other sensors separately primarily because of their use in industry. Welding requires the special application of sensor technologies which are currently in use, in some form, at virtually every robotic welding installation today. The second part of this section discusses other sensors which are used throughout industry in a variety of ways which are situation specific.

### I. WELD SEAM TRACKING

"Through the Arc" tracking provides guidance by oscillating the torch back and forth over the line of travel, checking for arc current or voltage variation, and adjusting arc length or distance to weld respectively. This concept has been adopted by industry in recent years. The newest technology applied to seam tracking is use of computer vision sensors to monitor weld conditions [12]. A video camera is focused on the weld seam and provides images of the weld bead, weld pool, and/or the solid-liquid boundary. This image is processed to yield control of the weld pool, width, weld quality, and the joint tracking by comparison and correction with computer control. The system can be single or multipass as described before, with the multipass used where geometry is difficult to program (as in three-dimensional applications). Single pass requires the system to operate in real time with the camera focused just ahead of the torch.

In order to view the weld, a vision system must be supplied with a light source. Special sources are required due to the inherent brightness of the arc. Structured patterns provided by conventional lights or laser sources coupled with visual algorithms to identify the patterns (and hence disturbances in them) provide the necessary feedback. Unstructured sources necessitate direct visual interpretation of the seam. A new vision-based system operates on the principle of infrared themography [13]. This system senses temperature distributions in the weld area which are extremely sensitive to weld conditions. Examination of arc positional error, seam variation, and contaminants in the weld path are possible. Electro-optical triangulation techniques are based on light pulses provided by a light source (usually photodiodes) which are decoded by a microprocessor to provide positional information.

## II. OTHER SENSORS

We have discussed sensors as applied to welding, but not in general. Sensors are used at most robotic installations even if they are nothing more than a limit switch to indicate part presence. Sensors can be divided into four broad categories:

1. Vision
2. Tactile and Proximity
3. Force
4. Miscellaneous

### 1. VISION

Visual sensors typically consist of a video camera, an image processor, and a microprocessor or microcomputer (see Fig. 11) [14]. Special lighting helps to minimize scene complexity. Light sources include:

a. Diffuse -- creates distinct shadows

b. Back Lighting -- creates silhouettes

c. Spacially Modulated -- creates stripes on an object which show as contours.

The vision system works by digitizing a scene through the video camera, pushing this information through algorithms to extract figures of objects, and sending some output signal to a computer for identification. With this information the robot may

--execute visual part inspection

--retrieve randomly oriented part from various conveyers and part feeders

--differentiate between objects (parts) in a particular scene

--guide control in complex assembly operations

--make dimensional measurements

--provide mapping of surfaces

--make range/speed calculations between object and sensor

--provide attitude information relative to a surface or object

--read codes or characters

Note: Some electro-optical devices are considered vision sensors because of their ability to sense light levels. If they are oriented in a specific way, they can do such things as read bar codes or characters and sense object presence.

2. TACTILE AND PROXIMITY

PROXIMITY--Various physical principles are used in proximity sensing; a summary follows [15]. These sensors can do such things as alert a robot to a potential collision, indicate part presence or act as a safety net to protect operators. The types of proximity sensors are:

a. Electro-optical -- including laser and L.E.D. applications

b. Eddy Current -- usually a transducer

c. Magnetic Field -- detection of variations

d. Capacitance -- radio frequency field detect intrusions

e. Microwave -- like police radar detects movement

f. Ultrasonic -- transducer and receiver detects distance

g. Infrared -- senses changes in heat; i.e., distance to, etc.

h. Vibration -- detect vibrations above/below preset level or presence/no presence.

TACTILE--Tactile sensors can be as simple as a switch on the end effector to indicate that contact has been made with an object or more elaborate designs emulating anthropomorphic characteristics [16]. In recent years research has proven that robot touch sensing is feasible. High resolution imaging touch sensors identify a part by its "feel" [17]. An array of pressure sensors (semiconductor material sensitive to pressure) located on the finger of a robot manipulator provide an image to a computer much like a vision system. The trade off in a device like this is between system sensitivity and range. Commercial use is limited so far since most designs are just passing out of the research stage.

3. FORCE SENSORS

Force sensors are mounted in a myriad of places, the most popular being the wrist mount. Most are constructed of some arrangement of strain gages to yield force and torque measurements. Force sensors coupled to a robot control and a compliant wrist (provides the robot with the ability to compensate for poor alignment) provide a flexible base to work from for many assembly jobs and inspection tasks.

4. MISCELLANEOUS

Voice sensors are a new idea and should prove useful in areas such as safety and remote programming and control. A human operator can command a robot operating in a hazardous environment or perform some task in conjunction with prompting a robot. Any device providing feedback could be termed a sensor; I have covered the sensors used in industry today and those currently being researched.

CONCLUSION

This chapter paper focused on the identification of robot end effectors and their respective supporting sensors. End effectors have one thing in common; they attach to robot wrists. The next section of this report concentrates on the robot wrist by discussing the design and construction of a prototype robot end effector exchange device.

## CHAPTER 2

## DESIGN OF A PROTOTYPE END EFFECTOR EXCHANGE DEVICE FOR A LIGHT ASSEMBLY ROBOT

### I. DESIGN CRITERIA

Design Criteria were derived from two primary sources; limitations imposed by the robot itself and requirements due to the nature of the end effectors. Further limits were derived by noting the fabrication techniques available as well as material limitations bounded by cost and manufacturability. Finally the design was decided to act as a prototype therefore allowing for revision and hopefully charting a new, more simplistic approach to the problem of robotic end effector exchange.

Each end effector has specific needs such as electrical power, pneumatic suction or sensory interaction to perform a desired task. Chapter 1 outlined the end effectors in use in the robotics field today and discussed each one's operating principles. The following list summarizes the requirements specific to each end effector:

| End Effector | Requirements |
|---|---|
| Hydraulic Grippers | 2 way hydraulic lines |
| Pneumatic Grippers | 2 way pneumatic lines |
| Vacuum Grippers | 1 way pneumatic line |
| Magnetic Grippers | 2 electrical lines |
| Arc Welders | 2 electric lines + wire feeder |

Spot Welders ------------------2 electric lines +
electrode control

Spray Coaters -----------------2 air/electric +
material feed

Electric Power Tools -----------2 electric lines

Heating Torch ------------------2 gas lines + control

Pneumatic Tools ----------------2 way pneumatic lines

Glue Guns ---------------------2 electric + glue feed

Sensory Requirements

Through the Arc Welding Sensor -- no additional lines

Vision System -- 2 to 16 elec. lines if wrist mounted

Tactile/Proximity/Force -- 2 to 16 electric lines

Voice -- usually unrelated to end effector

The robot available for the study was a Unimation Puma 560 which is a six axis (all rotational joints) light duty all purpose robot. It has approximately an eleven pound payload capacity forward of the wrist flange. This means that end effector, exchange mechanism, and the payload must total eleven pounds. This provides the first bound for design; i.e., that we minimize weight to allow for greater payload and/or heavier end effectors. The wrist flange is a two-inch diameter circle with four tapped mounting holes (see Fig. 33) which are inaccessible from the robot side. To minimize problems with clearance and coupling, the wrist mounted part of the device was limited to the two-inch diameter circle. Attachment for the prototype would have to be by threaded fasteners inserted from the device side.

The electrical needs were limited to the use of low voltage lines for several reasons: High voltage lines are large in size (as are their connectors) and pose a threat of interference if not properly shielded. They also require more caution in coupling/decoupling since they may accidentally come in contact with humans or conductors risking electrocution or a short. Low voltage lines are small in size and require much smaller connectors. They can be used to control higher voltage devices by routing the larger lines directly to the tool and using smaller lines through the wrist to control the tool through optical or electrical relays.

Pneumatic needs for all end effectors are fulfilled by two way air lines. Hydraulic grippers were ruled out due to their lack of popularity in this class of robot (in particular the Puma uses a pneumatic gripper so this stipulation was essential). The advantages to using air as opposed to hydraulic power stem from the messy nature of hydraulics in sealing. This inherent problem would provide for a complex seal design so as not to soil the work area upon coupling/decoupling. Air, on the other hand, can be vented directly to the atmosphere with little risk.

Special needs such as wire feeders, gas lines, paint and glue feeders, were not accommodated through the wrist. Applications requiring such specific needs can be treated as the high voltage tools were; i.e., use low voltage lines to switch end effector mounted feeders, gas supplies, paint lines, etc., through relays or solenoid valves for liquids.

Now that the mechanical and electrical criteria had been established some of the practical limitations in constructing a working prototype were added. The usual minimal cost, reliable design, low maintenance, and ease of manufacturability were added; but also added were stipulations specific to this problem. The criteria had to be tailored to allow for manufacture by available means. Aluminum was chosen as a fairly inexpensive, light weight and machinable material. Upon researching the few past designs for a part like this, some common aspects were eliminated which helped formulate the following design objectives: First, coupling should be a simple mechanical action (i.e., no motors, solenoids, etc., common to past designs). Second, a positive, fail-safe lock should be established upon coupling. Third, electrical connectors should remain enclosed inside the device to provide protection (some designs today mount the connectors on the outside). Fourth, the design should be easy to scale to facilitate use on different sized robots.

## II. PROTOTYPE DESIGN

Upon completion of the design criteria and objectives, the next logical step in the design process was to construct a prototype. Many mechanical locking systems were considered before chosing the simple interference fit arrangement used for the prototype. Linkage systems were ruled out due to the number of parts, as were gear and clutch, and cam mechanisms. Threaded locking systems (such as the bayonet) require complex and hence expensive fabrication practices. A simple ball detent (see Fig. 22) provides a positive fail-safe lock capable of self centering on a hole and allows for easy release. A spring plunger (see Fig. 23) is an adaptation of a ball detent with the exception of a tapered rod in place of the ball. This rod provides greater penetration for a more secure lock and "seeks" holes more efficiently. (See Fig. 16 and 17 for spring plunger location).

After settling on spring plungers as ideal for locking, next considered was the necessary part geometry to allow for locking and release as well as space for pneumatic and electrical needs. The most natural coupling arrangement mimics many electrical connectors in that a male pin is inserted into a female cavity. A cylindrical shape was chosen originally for ease of manufacture and adherence to the wrist flange circular limit, but later also proved beneficial for pneumatic sealing. The two-inch diameter circle of the wrist flange limited the area to mount concealed electrical connectors if they were to be aligned axially with the overall coupling direction. It was further decided to use commerically available connectors in the prototype and a search for the smallest computer signal line compatible connectors led to the use of the industry standard "D-Subminiature" connectors (visible in Fig. 16). Since sixteen lines were the desired maximum for sensory needs and two more lines were desired for switching various tool/material feeder arrangements, the entire need totaled eighteen. Two nine contact D-sub connectors proved optimum to occupy the least frontal surface area and carry the electrical requirements. They were screwed to steel plates (see Fig. 18) which in turn were screwed to the coupling bodies (see Fig. 16). Sealing around the electrical connectors was ruled out as was any axially mounted pneumatic connectors, due to space limitations instilled by the forward mounted connector plates. Still needed was a method to secure the male part (wrist mount) inside the female (end effector mount) both axially and torsionally (the connectors repel rotation; however, they provide no positive lock). The details of the male part can be seen in Figures 12 and 13. The details of the female part are included in Figures 14 and 15. To settle both problems simultaneously, a pneumatic cylinder arrangement with three o-rings was used. This provides a stable base, and with the addition of a radially mounted spring plunger, a positive lock. The three o-rings divide the radial normal mating surface into 2 airtight compartments to allow air passage between couplings. Holes were drilled axially and accessed radially with the outer radial holes threading to brass hose barb fittings. Details on air passages can be seen on Figures 12 to 15, o-rings are shown on assembly drawing in Figure 16.

The spring plunger provides a fail-safe lock which can only be released by a pin pressed through the access hole on the outside surface of the female coupling. Two circular grooves on the outside of the female part (consult Figures 14 and 15) engage the side plates of the decoupler (decoupler parts in Figures 19 through 21) for support. One of the plates has a vertically mounted pin which presses through the access hole to release the spring plunger.

This design was created with the aid of a CAD system which provided visual and mathematical verification of the often critical geometric limits encountered in designing this compact a device. The entire device is depicted in the photo section. appendix figures (see Figs. 12-21). This particular design can be interfaced to many of the existing "light duty" robots in use today which incorporate pneumatic grippers. Many "medium duty" robots can also benefit from the device if their payload capability is within reason of the material failure limits of the wrist flange mounting area. The design can be easily scaled to allow for use on the "heavy duty" class robot. The following section deals with the operation and testing of the prototype.

## CHAPTER 3

## TESTING OF THE PROTOTYPE

Testing began by writing a VAL program (Puma robot language) to command the Puma to couple and decouple the device (see series of photos in photo section) repeatedly. The base of the decoupler was clamped to a wooden table and the table attached to the base of the robot. The table proved to be only semirigid and added to any of the robots accuracy error. The cyclic couple/decouple routine proved the device to function about 80 percent of the time. Problems arose in two chief areas: first the repeatability and accuracy of the particular Puma were below specifications; second, the table was inherently unstable and hence did not provide a firm base. Lifting the coupled device out of the decoupler cradle was no problem during testing due to the more generous tolerances afforded in this interface. The problem with the coupling/decoupling really arose when the robot pulled the male part out of the female, jamming occurred and they could not be separated. Subsequently, a test to find the forces and moments at critical jamming angles was performed. Angular misalignment is only a problem in the vertical plane since the horizontal plane alignment can be compensated for in the clamping of the base to the table. Two tests were performed: one to find the decoupling force for no angular misalignment, and at the critical jamming angle with no momement applied. The second test was to find the moment necessary to cause jamming. Both tests considered both the angle above and below the neutral axis. Figure 24 shows the force test. A known weight (W) is attached to a line over a pulley and fastened to the male part. The pulley can be moved to vary the angle theta (theta equals zero is the neutral axis). Results were derived from tests varying theta and increasing the known weight necessary to release the male part. Figure 25 shows the moment test. Again, the known weight and line with pulley and variable angle were used; however, this time a bar was attached to the male part (length r). Hence as the angle theta increased a moment was added to the coupling (angle $\Theta$ and moment M are shown in Figure 25). Results and error calculations can be found in the Appendix.

The force test was conducted in the following manner. For each angle theta in one degree increments weight W as increased until the male part pulled cleanly free of the female part. This procedure was repeated ten times for each degree. Results from this test showed that for no angular misalignment (theta is zero) the average force to uncouple the device is 6.68 + or - .14 pounds. The angles where jamming first occurred were -11.5 + or - .56 degrees and

+13.5 + or = .56 degrees. The force to release just before the jamming occurred was 7.42 + or - .14 pounds. The error bounds for the forces were derived from three sources: error in determining actual release, error in weight measure, and error in weighing the cable system. These errors were all expressed as tolerances in weight measure and an error analysis was performed (see Appendix) to find overall error.

The moment test followed the same format as the tension test with ten tries per one degree increment. Results show the positive moment to be much higher until jamming occurs, or 4.21 + or - .278 in-lb. compared to the -.652 + or - .185 in-lb. moment required in the negative direction. The same is true for the jamming angles, with +13.0 + or - .56 degrees before jamming occurs and only -2.0 + or - .56 degrees allowable in the negative direction. Error analysis for the moment test cited additional error in reading the moment arm distance as well as using the three sources established in the force test.

Angular error for both tests was calculated with sources derived from: reading of angular measurements poorly and poor leveling of the neutral axis.

The test results show that for robot angular misalignment in the vertical plane with respect to coupling there is little tolerance in the negative direction. Also shown are the low forces necessary to decouple the part.

Having tested the coupling function next the pneumatic and electrical interfaces were tested. Both functioned flawlessly with the exception of some leakage around the spring plunger. The design should include another o-ring to separate the spring plunger from an air cavity.

The testing of the prototype led to several recommendations: First, use a steel table as the base for the decoupler. The dimensional tolerance to couple the device requires a totally rigid fixture. Second, use a brass insert rather than the nylon one specified in the drawings. The nylon could not stand up to the coupling forces as the manufacturer claimed. Modifications called for turning a brass insert on the lathe. Third, don't use wrist compliance to compensate for poor robot accuracy/repeatability or an unstable table. This will add to robot inaccuracy in performing tasks.

# CHAPTER 4

# DESIGN FOR PRODUCTION

Today, many material/process selections face the design engineer. The choice is sometimes more of an art than a science. Many factors enter into the selection process including product demand, quality life, difficulty of manufacture, and mechanical properties such as strength, geometric tolerance, and machinability. It is not the purpose of this next section to choose an ultimate solution but rather to cite the options available.

A review of possible metal working methods and plastic forming techniques possibly suitable for the production of the end effector interchange mechanism follows. [18, 19, 20] The last part of the discussion will cover design revisions and ideas to further ready the part for automated production.

I. METAL WORKING

POWDER METALLURGY - This process involves preparing a fine metallic powder, pressing the powder into the desired shape, and heating the resulting part (sintering). The final mechanical properties are a function of the powder density and usually are somewhat less than that of a wrought part. Parts are best suited for this process if they have a length to diameter ratio less than two, although it is not essential. An almost uniform cross section is required or else a complex set of dies are needed since they must apply great pressure to the part. Never can a hole be created perpendicular to the axis of compaction. This last stipulation means that machining for the radial holes and for any grooves would be required, tapped holes also would have to be created after the part was molded. Due to the cost of the die (assuming one can be constructed) a production minimum of 10,000 parts can be invoked to insure economic profit. This stipulation plus the obvious problems with the part geometry coupled with machining needs after molding led to the opinion that this process was ruled out.

SAND CASTING--The procedure calls for constructing a two-piece mold by packing sand around a pattern in the shape of the part to be made, connecting the cavity left with a sprue hole for metal to be poured from the outside, and pouring molten metal into the hole.

Design of parts for sand casting demands knowledge of shrink and distortion allowances caused by cooling metals, and limitations in molding interior cavities. It is possible that the parts in question could be cast this way however due to low dimensional tolerancing and limitations in casting interior cavities machining after casting would be essential.

SHELL MOLDING--The process also uses sand but this time mixed with a plastic binder. This mix is poured over a metal pattern of the part to be created and cured in an oven. The pattern is then removed by cutting off the shell. The shell is glued back together and supported by sand and molten metal is poured into the shell. Tolerances of .003-.005 in. are possible. This tolerance could be within the value necessary for the mating surfaces given that larger o-rings were employed. Again, problems arise in the creation of complex cavities as in the male part, probably a fair amount of machining would be required to complete the part.

FULL MOLDING--A polystyrene pattern is created and covered with sand. As metal is poured into the pattern, it is vaporized and only the part is left to cool. This procedure is common for making very large parts with tolerances that are not too critical. It is not well suited for small parts creation.

NONFERROUS PERMANENT MOLD CASTING--This casting process is used primarily for simple parts and is just as the name implies: A steel mold is used to cast aluminum, magnesium, or copper-based alloys. The tolerances possible are .005 to .010 in. which are not within the part's limits. This coupled with the size limitation renders the casting method inadequate.

DIE CASTING--Like permanent mold casting this is also for nonferrous materials. The difference is that the metal is forced into dies under pressure and held that way while it solidifies. The dies are expensive but provide good dimensional accuracy, and surface finish. Cores can be used to make interior features which could prove ideal for the part in question. However, initial cost is high so that mass production is essential for economic reasons.

CENTRIFUGAL CASTING--Spinning a permanent mold for cylindrical objects with a hollow center. This works well for pipe but is not too well situated for objects as complex as the end effector interchange device.

INVESTMENT CASTING--This casting process is begun by making a master pattern of wood, plastic, etc., and making a master die of metal from the master pattern. Wax patterns are then created from the master die and assembled on a common sprue. This whole assembly is then coated with investment material (plaster with fine silicaceous material) and the wax pattern is melted out. The resulting mold is then preheated and metal is poured in. This method is expensive but good for complex shapes with tolerances from .005 to .010. It is possible that investment casting could prove feasible in the manufacture of the device; however, it may still prove costly compared to machining the part from stock.

SHAW PROCESS--The process is the same as investment casting except that a gel is used to cover the wax patterns and can be stipped from them and still retain its shape later. The special gel is then heated and allowed to harden. Tolerances of .002 to .010 in. are possible.

II PLASTIC MOLDING

There are two categories of plastics most commonly used in plastic forming operations: Thermosetting plastics which use heat to cure, and thermoplastics which cool to harden. Each plastic has different mechanical properties specific to its name. The following table lists plastics with properties that may make them useful in molding the end effector interchange device.

| Thermosetting Plastics | Thermoplastics |
|---|---|
| Alkyds | ABS |
| Epoxies | Acetals |
| Phenolics | Cellulosics |
| | Polyamides |
| | Polycarbonates |

All the plastics listed show superior dimensional control in molding with decent tolerances and good surface finish with respect to competitors. Plastic has the advantage of being light in weight, an electrical insulator, easy to fabricate and low in material cost. It has a high strength to weight ration and a low coefficient of friction. All of these properties are advantageous in building the project parts. A few disadvantages arise; poor heat resistance, tendency to age, high coefficient of thermal expansion, and poor dimensional stability when compared to metals. One item of particular interest is the ability for some plastics (ABS for example) to be electroplated which could allow for the couplings to have integral electrical connectors.

Plastics can be molded in various other ways than the three listed below; however, these three prove to be the useful ones for creation of the design. Obviously, we are looking for high dimensional accuracy as well as good surface finish for the mating surfaces.

INJECTION MOLDING--Molding takes place by applying heat and high pressure to fluidized granular thermoplastics forcing them into a metal mold cavity, where they are ejected after a short period of time. Molding of this sort is highly accurate within the material limits and can be used to form complex shapes.

JET MOLDING--This is the same as injection molding except that a heated mold cavity is used to cure a thermosetting resin.

COMPRESSION MOLDING--This method is analogous to powder metallurgy techniques in that a granular thermosetting resin is placed in a mold cavity of desired shape. The mold is heated and the amount of granules are always greater than what is needed to insure there are no pockets in the finished product. This process is usually inferior to injection or jet molding.

## III. Design for Production Conclusions

Injection molding plastics stands out as the simplest way to create the features necessary for the part design. Integrally molded air passages, hose barbs and connector assemblies are possible. A possible design (see Fig. 26) includes smaller male and female couplings with a molded locking tab arrangement. The tabs lodge in grooves in the male part, and the rectangular peg is inserted into the central cavity which provides for torsional support. This peg could be molded as a keyed tapered cone or another polygon shaped object. Perhaps guided pegs and tapered holes could be used for alignment also. The design shown (Fig. 26) uses a decoupler with tapered arms to force the tabs out of the groove (decoupler shown in Fig. 27). A similar setup calls for barbed tabs securing the couple from the inside with forced release (see Fig. 28). Decoupling for both cases is similar to the original design with the part lowered on to the decoupler plate to unlock it.

End effectors attach the same way as in the prototype. Threading molded plastic may not prove strong enough so threaded aluminum inserts could be molded into the front of the end effector side of the device. The electrical connectors are molded subassemblies in the design shown (see Fig. 29 for detail) small sockets exit to the outside to interface with external devices. Larger tapered pins and sockets provide more contact area and higher strength in the critical coupling area. The internal detail consists of stamped one piece contact and leads from copper. If possible, the whole contact could be molded into the piece without a separate subassembly. Other connector choices include molding spring loaded contacts (see Fig. 30) directly into the mold, or using copper strips (see Fig. 30) molded in for contacts, or if possible use a metalicized plastic connector molded integrally. If the prototype arrangement including separate connector plates is desired (possibly necessary for use of standard connectors), then at least the body could be molded of plastic and include integral rivet-like pegs that could be staked or melted to hold on the connector plate (see Fig. 31).

Standardization for use with other robots in the puma 560 class involve interfacing the male mounting surface to other robot wrists. The most logical scheme suggests using enough mounting holes in the flange to accommodate each different robot. Another idea calls for an adapter to be fastened to the flange of the interchange device specific to each robot's needs (see Fig. 32).

Use of the device in different class robots; i.e., both higher and lower payload capacity robots, would require scaling of the design to dimensions proportional to the robot's size. This particular design lends itself quite well to scaling up. A larger device means more room inside for air passages, connectors, and locking devices. A smaller device requires further compaction of the internal elements.

two finger
pivotal single gripper
with external grasp

two finger
pivotal double
gripper with
external grasp

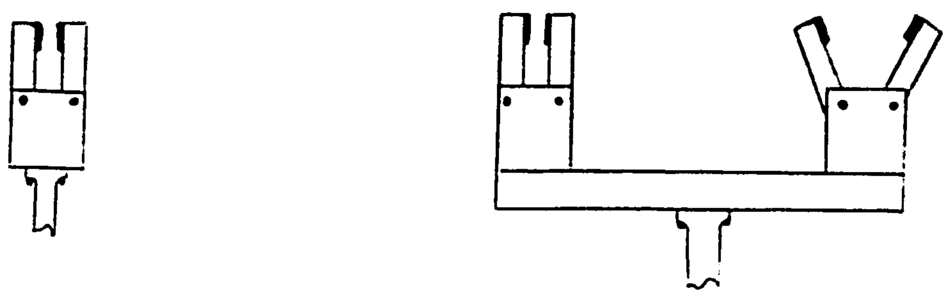


figure 1

two finger pivotal single
gripper with internal grasp

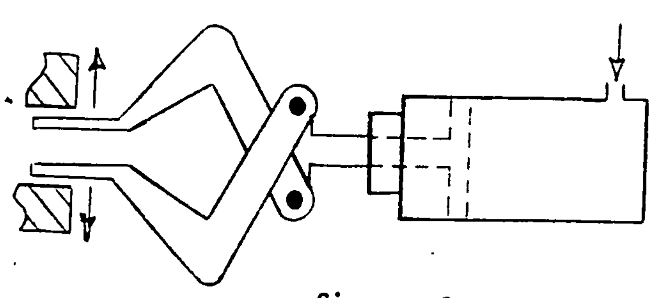
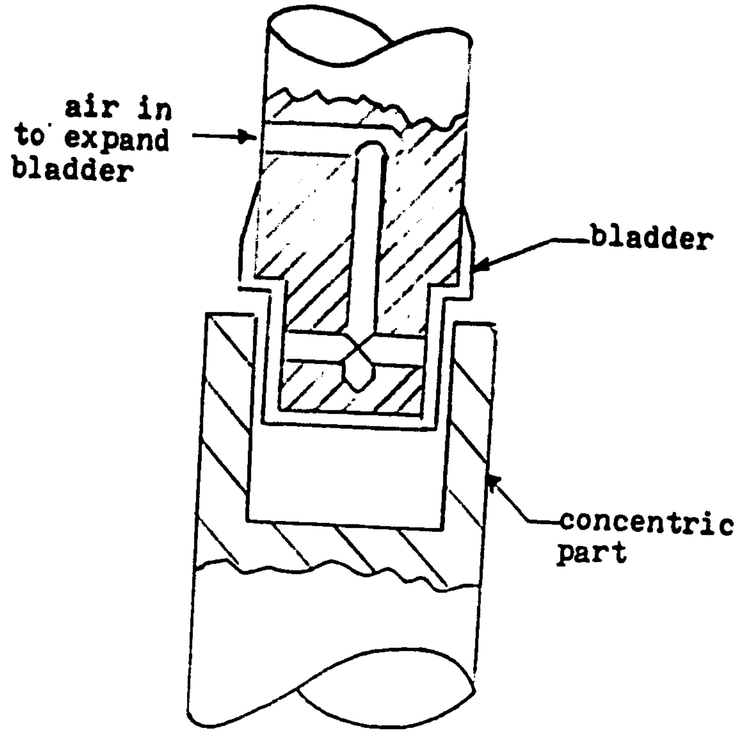
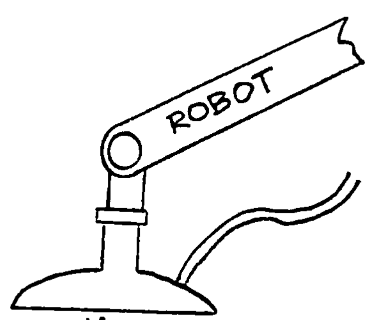


figure 2



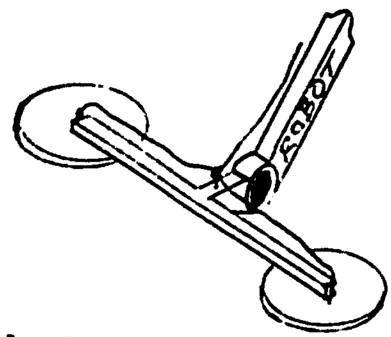

pneumatic internal expanding
bladder gripper

figure 3



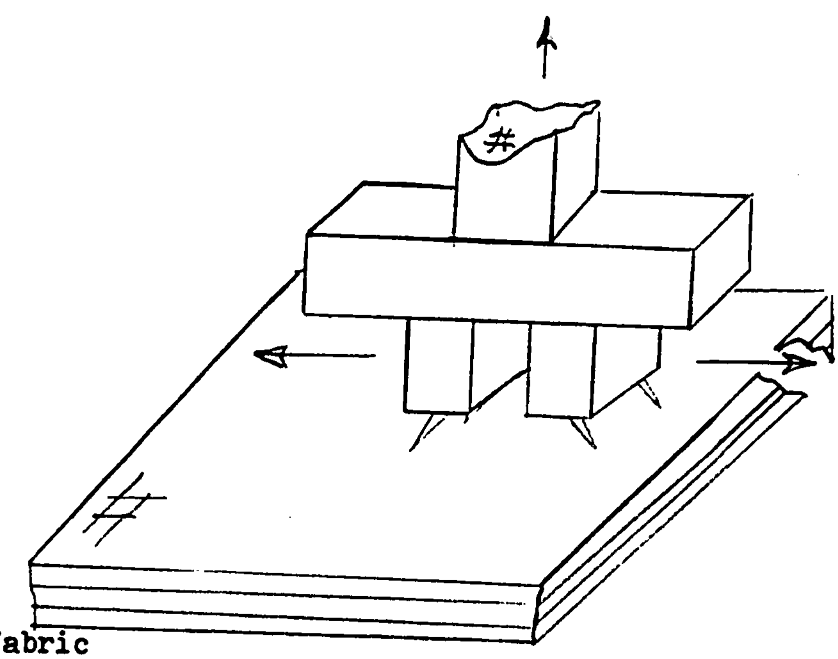

single suction cup vacuum
gripper

figure 4



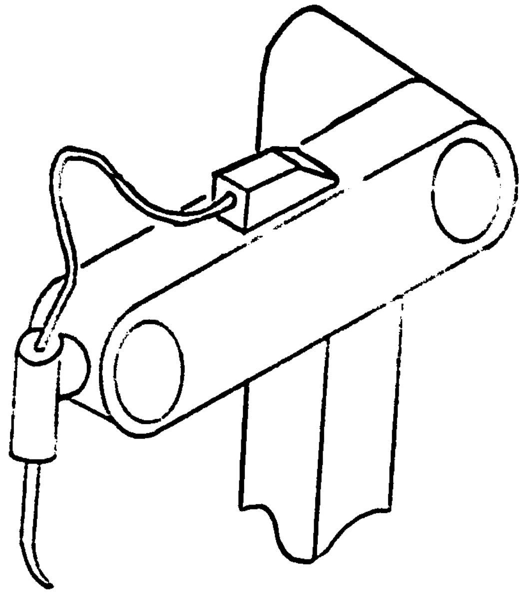
dual electromagnetic gripper

figure 5



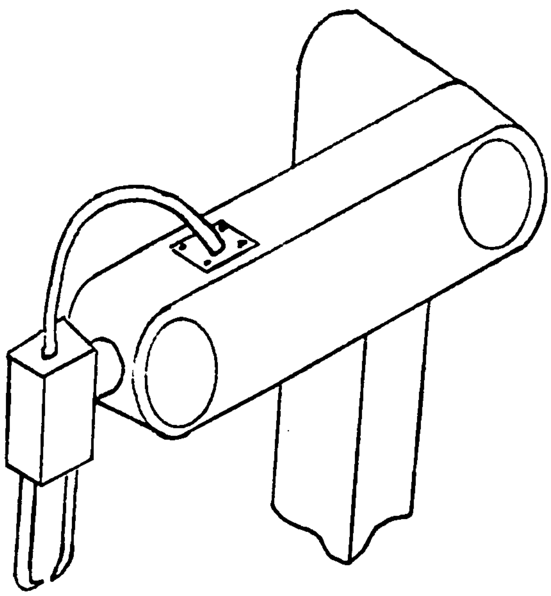
fabric
gripper -- separates sheets of material

figure 6



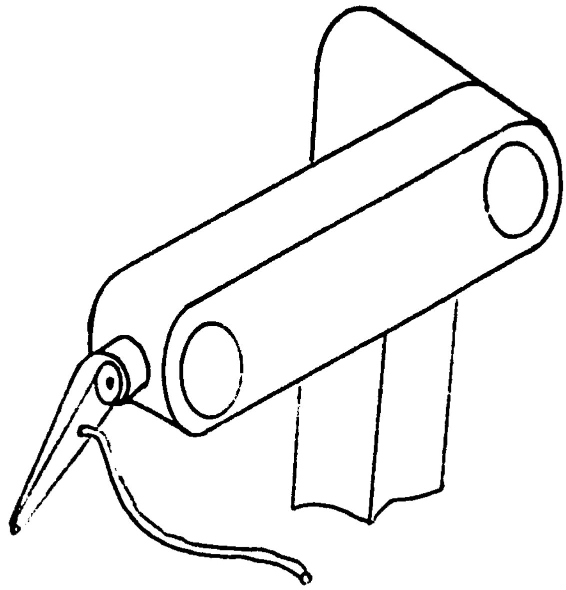
robot with arc welding end effector

figure 7



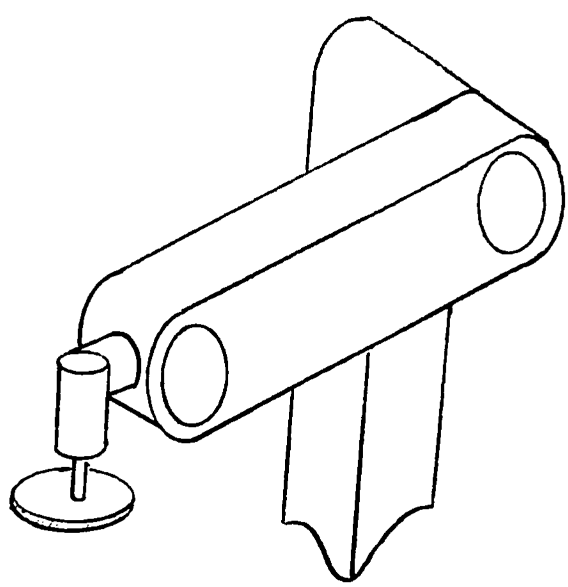
robot with spot welding end effector

figure 8



robot with spray coating end effector

figure 9

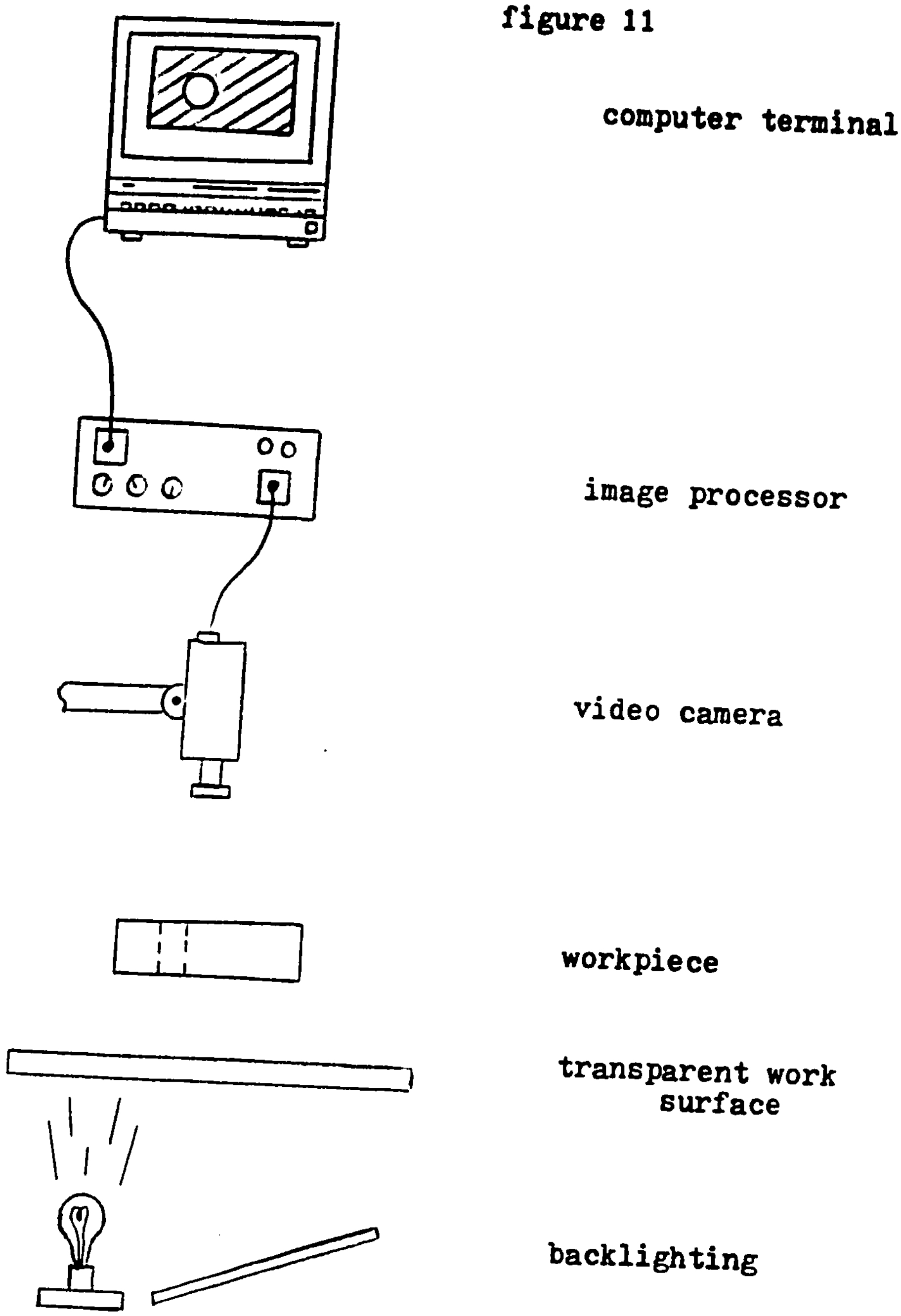


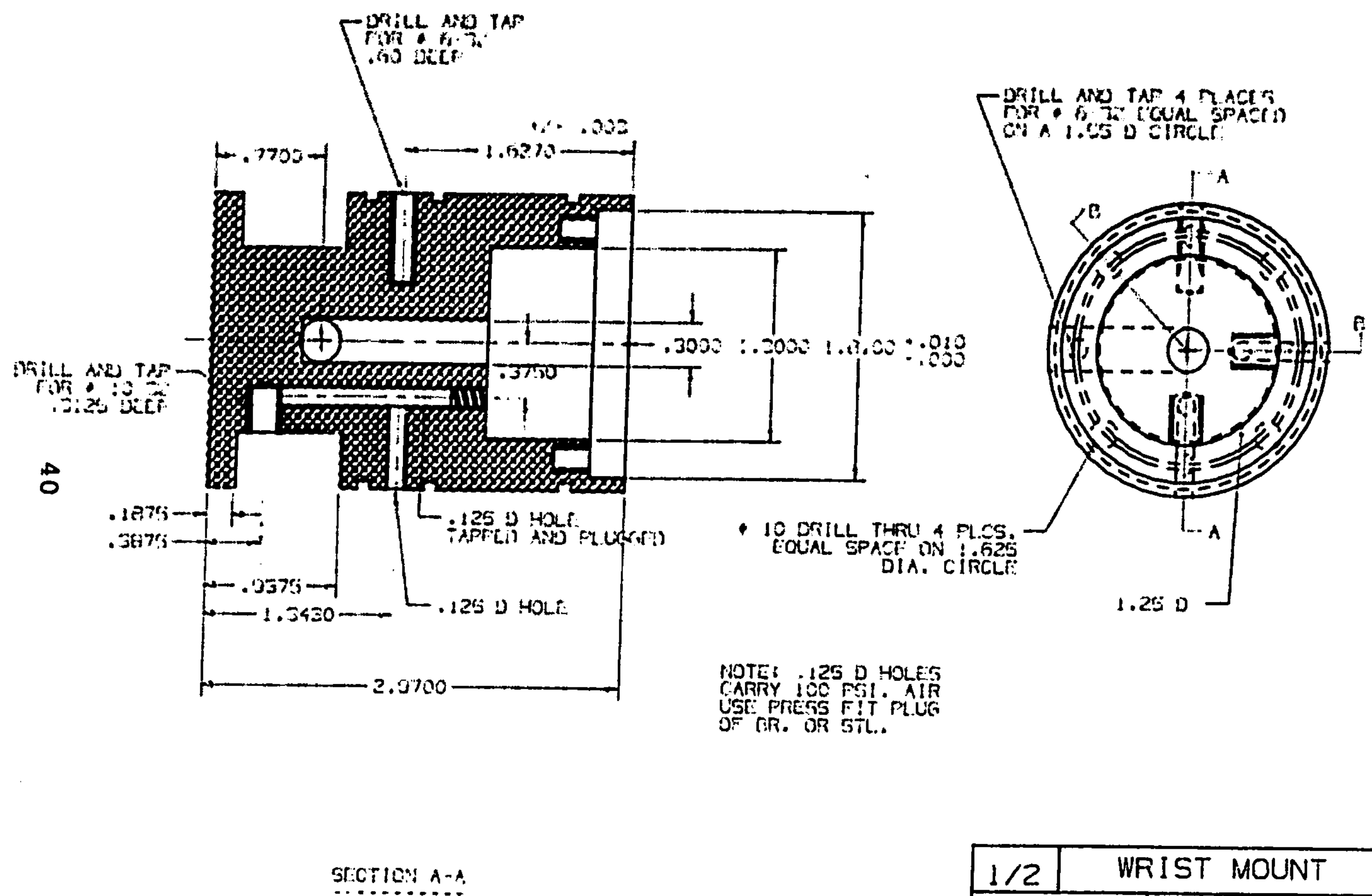
robot with grinding end effector

figure 10

BACKLIT VISION SYSTEM CONCEPT

figure 11






| 1/2 | WRIST MOUNT |
|---|---|
| DR/DSGN: D.L. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED

PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 12

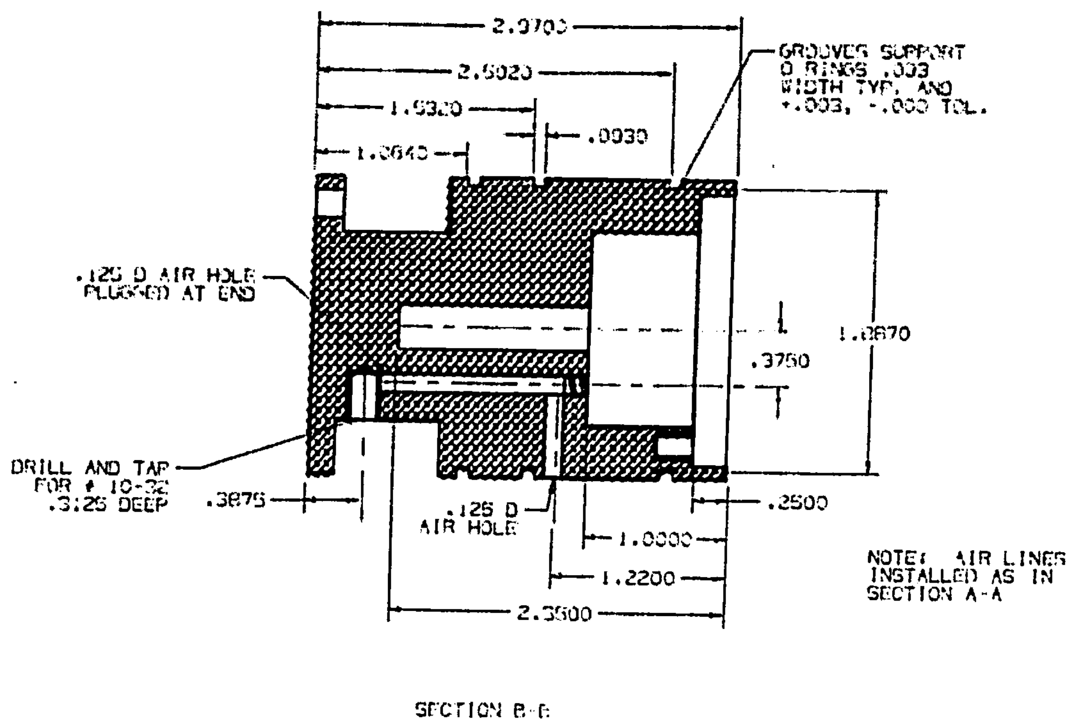



figure 13

| 2/2 | WRIST MOUNT |
|---|---|
| DR/DSGN: D.L. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED

PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

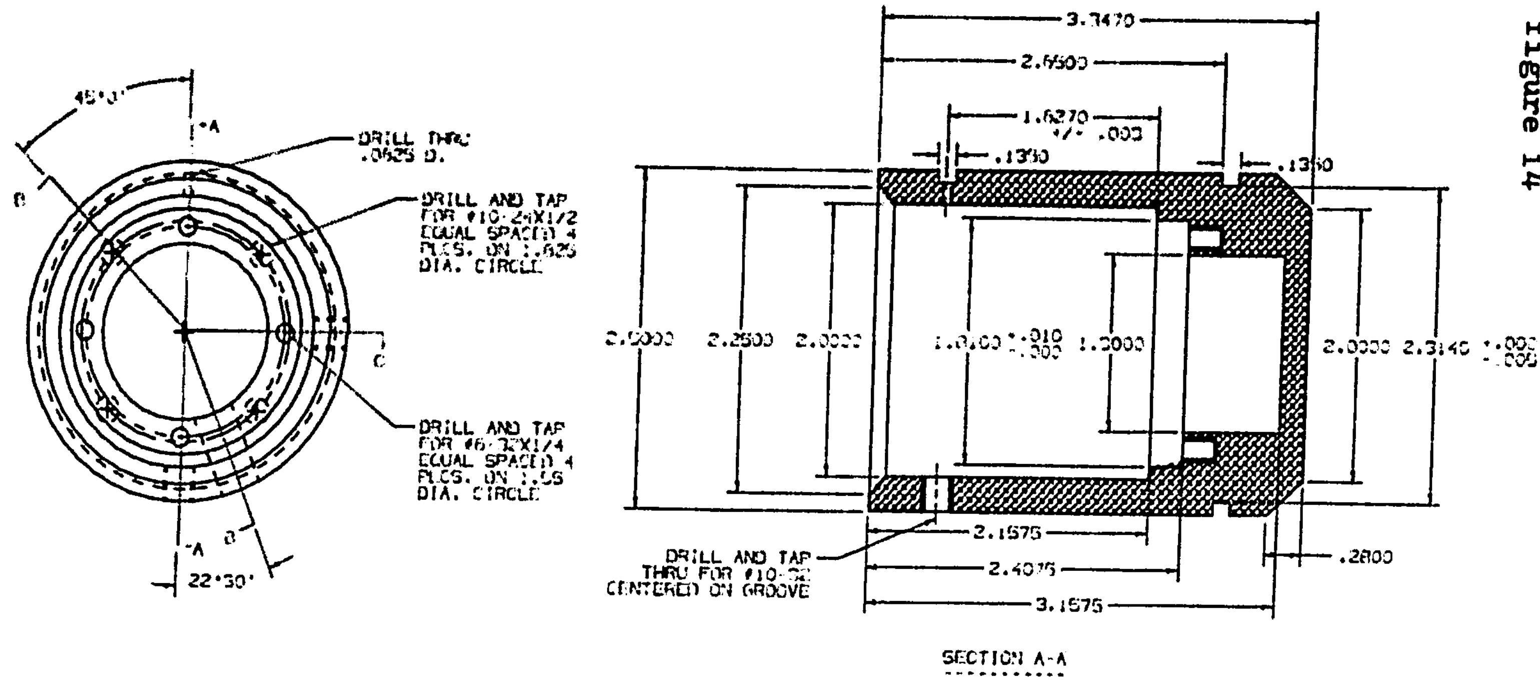
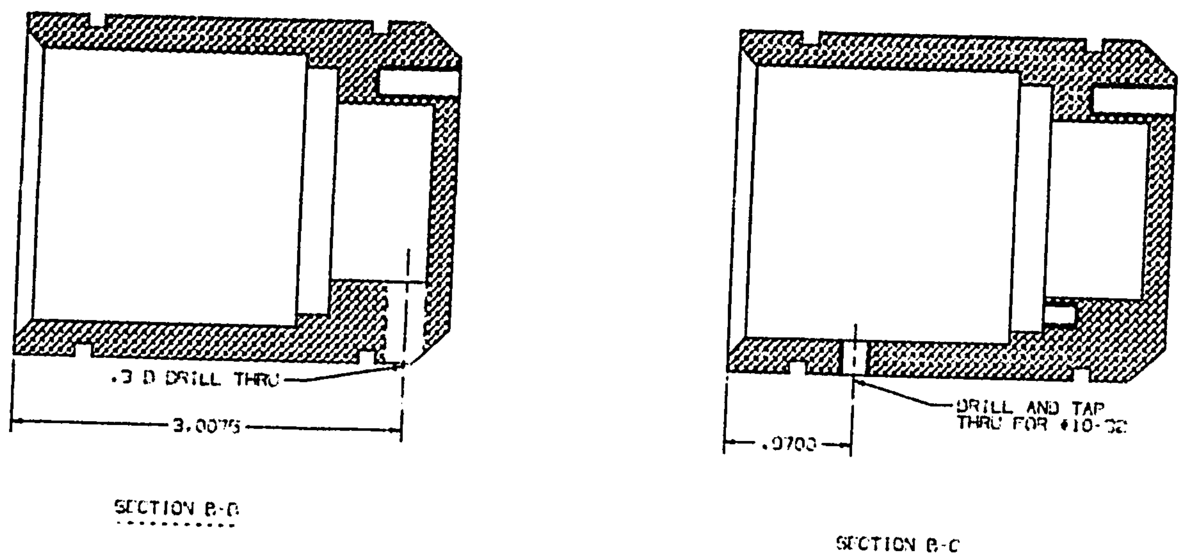



figure 14

| 1/2 | END EFFECTOR MOUNT |
|---|---|
| DR/DSGN: DL. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED




| 2/2 | END EFFECTOR MOUNT |
|---|---|
| DR/DSGN: D.L. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED

PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 15

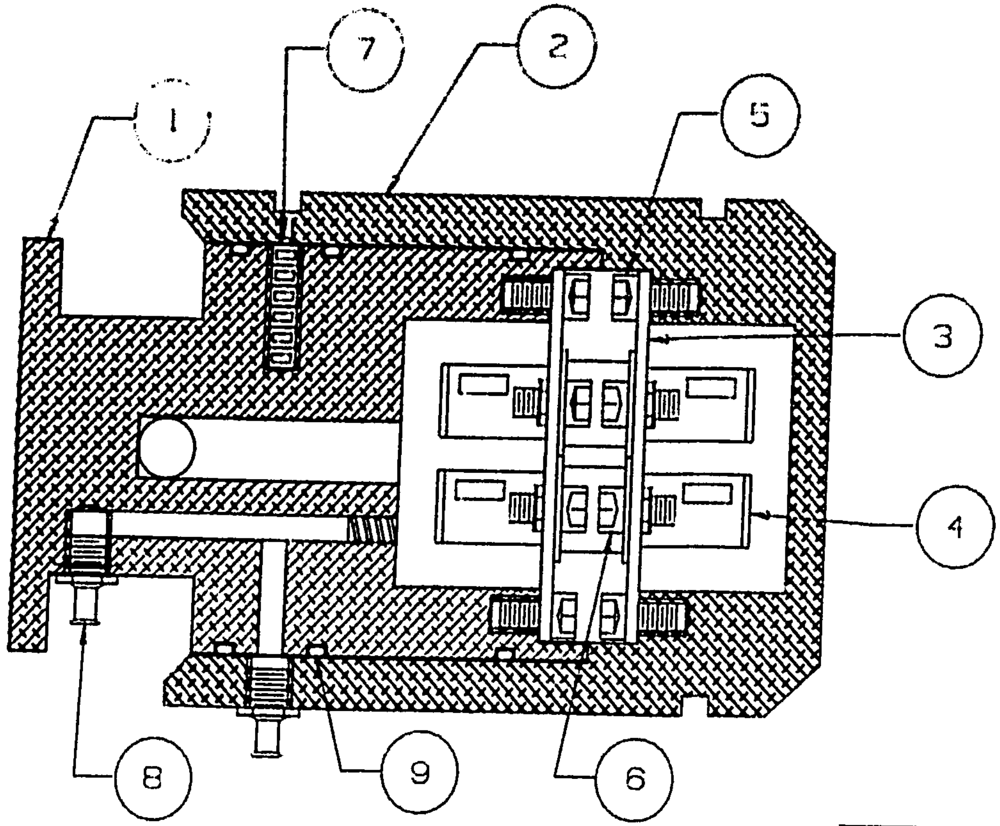



figure 16

| | |
|---|---|
| 1/1 | INTERCHANGE ASSEMBLY |
| DR/DSGN: D.L. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED

| | | | |
|---|---|---|---|
| 9 | NITRILE COMPOUND O-RING | 3 | RUB |
| 8 | #10-32 X .3125 HOSE BARB | 4 | BR |
| 7 | SPRING PLUNGER W/ NYLON TIP | 1 | STL |
| 6 | #6-32 X 1/4 HEX HEAD SCRW / NUT | 8 | STL |
| 5 | #6-32 X 1/4 HEX HEAD CAP SCREW | 8 | STL |
| 4 | D-SUB. 9 PIN CONNECTOR | 2 | -- |
| 3 | CONNECTOR PLATE | 2 | STL |
| 2 | END EFFECTOR MOUNT | 1 | ALUM |
| 1 | WRIST MOUNT | 1 | ALUM |
| PART NO. | PART DESCRIPTION | QTY | MATL |

| | |
|---|---|
| 1/1 | ASSEMBLY KEY |
| DR/DSGN: D.L. | LEHIGH U. 8/84 |
| FULL SCALE: INCHES<br>TOL. +- .010<br>UNLESS SPECIFIED | |

PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 17

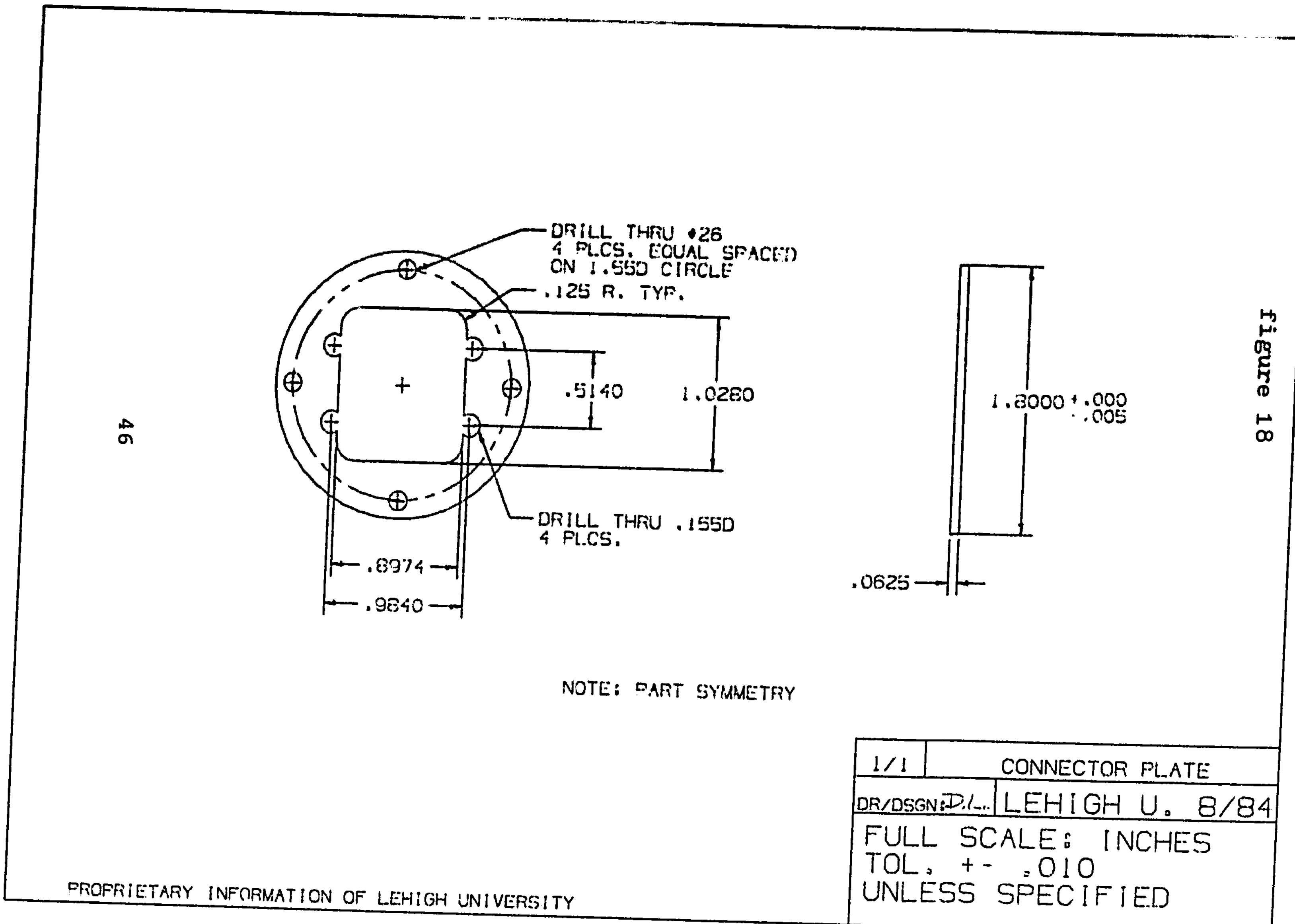
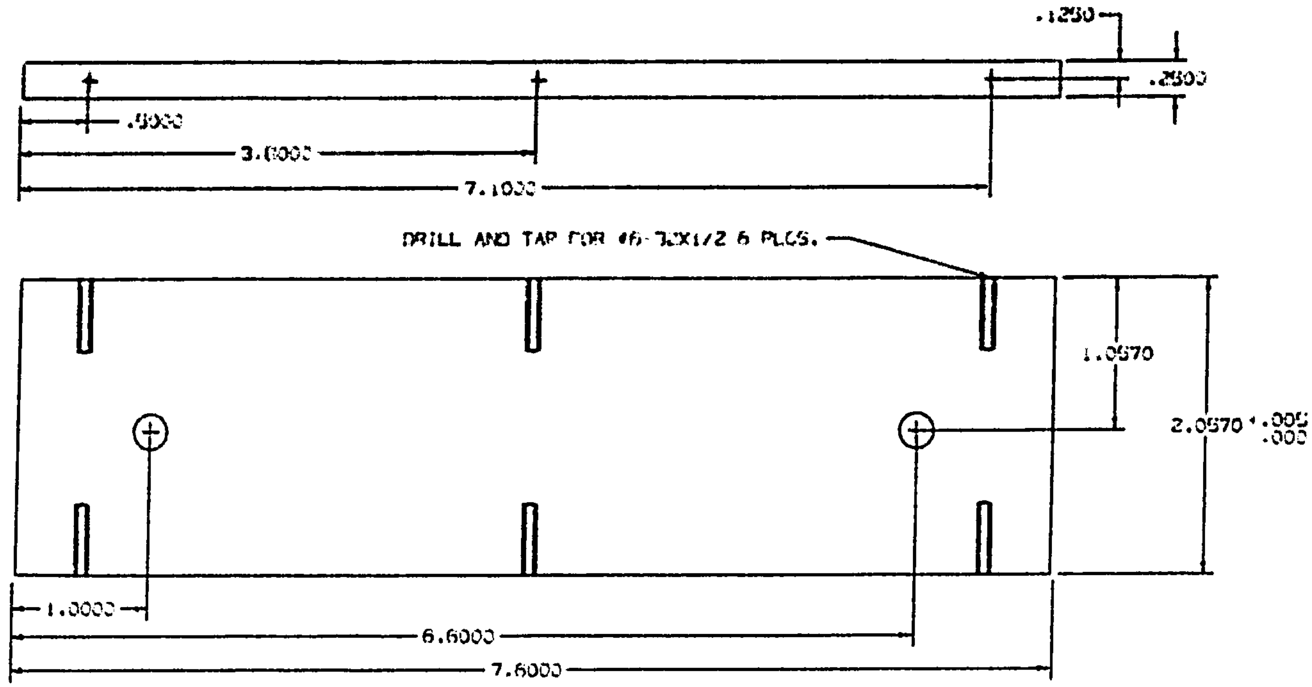

DRILL THRU #26
4 PLCS. EQUAL SPACED
ON 1.55D CIRCLE
.125 R. TYP.
.5140
1.0280
DRILL THRU .155D
4 PLCS.
.8974
.9840
1.8000 +.000 -.005
.0625
NOTE: PART SYMMETRY
1/1
CONNECTOR PLATE
DR/DSGN: D.L.
LEHIGH U. 8/84
FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED
PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 18



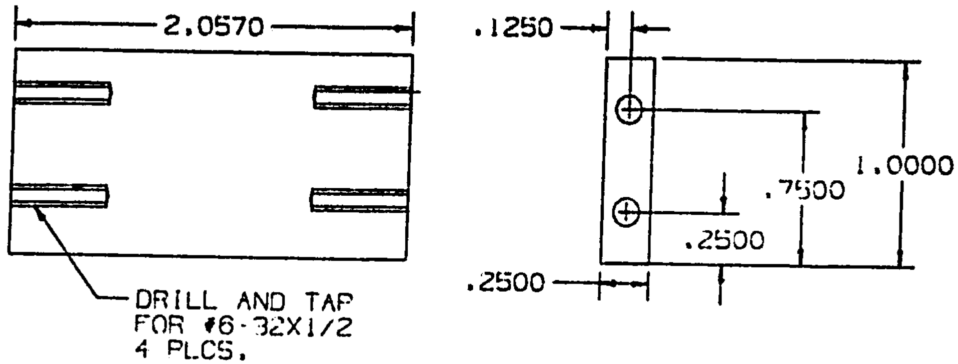

| | |
|---|---|
| 1/1 | BASE PLATE |
| DR/DSGN D.L. | LEHIGH U. 8/84 |

FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED





figure 19




| | |
|---|---|
| 1/1 | SUPPORT PLATE |
| DR/DSGN: D.L. | LEHIGH U. 8/84 |
| FULL SCALE: INCHES<br>TOL. +- .010<br>UNLESS SPECIFIED | |

PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 20

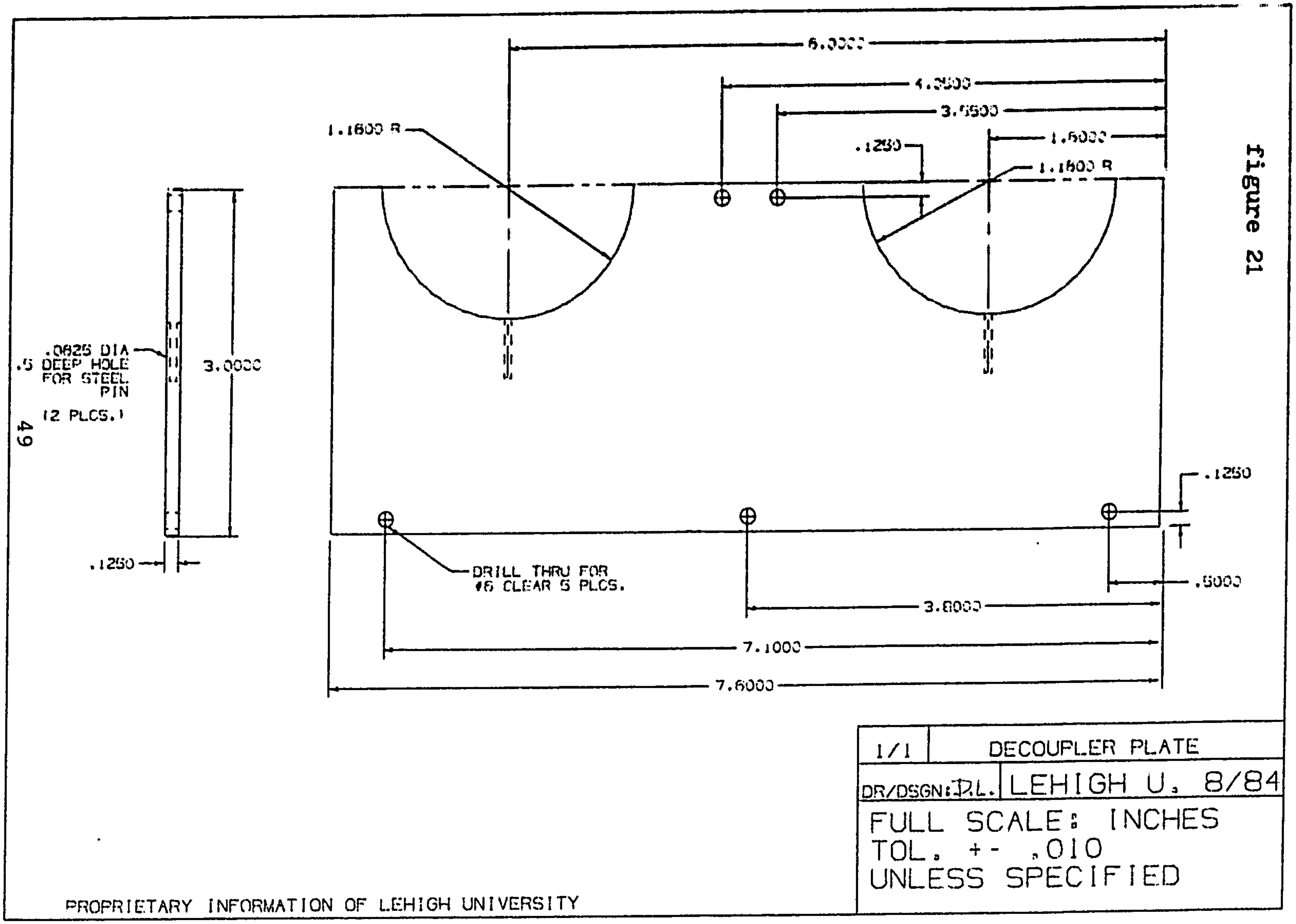
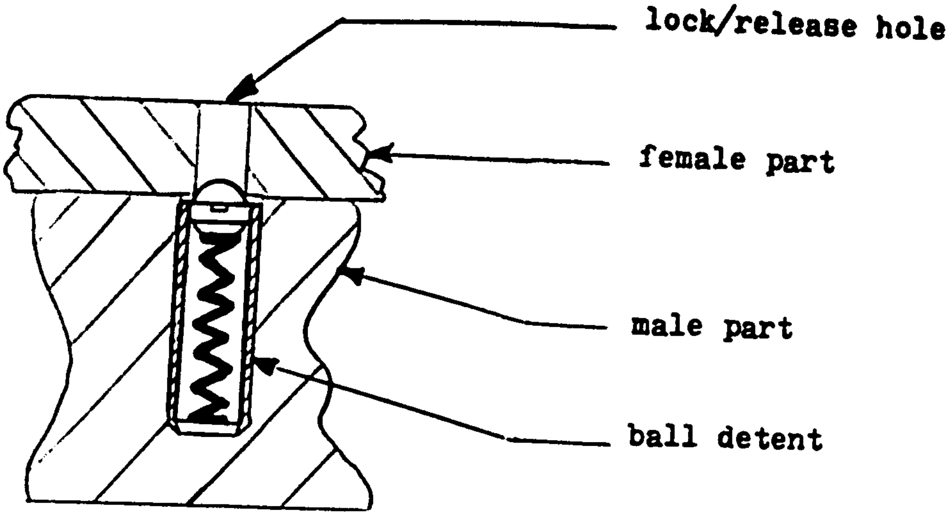
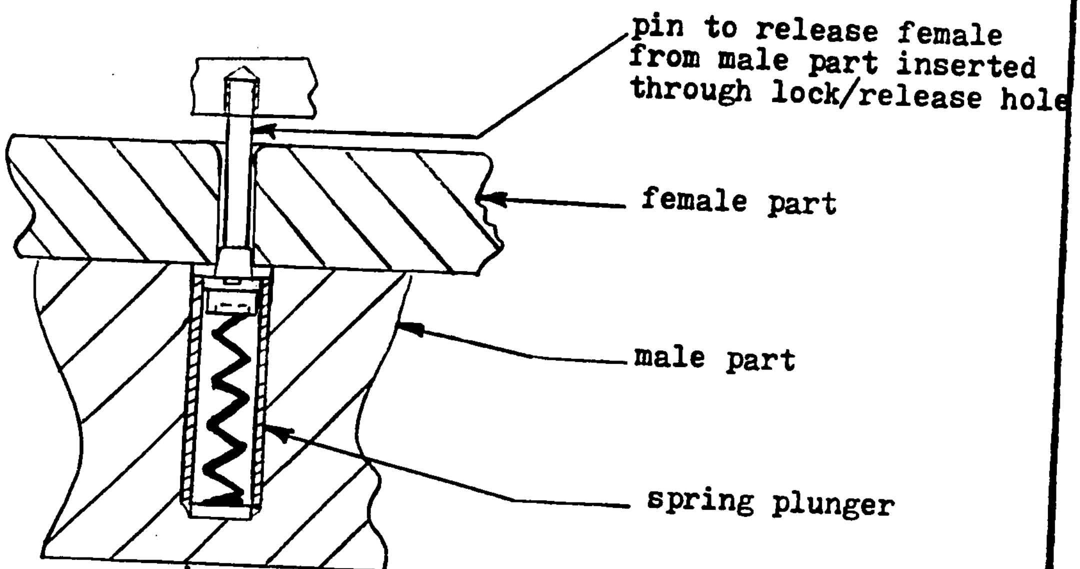

6.0000
4.3500
3.5500
1.6000
1.1600 R
.1250
1.1600 R
.0825 DIA
.5 DEEP HOLE
FOR STEEL
PIN
(2 PLCS.)
3.0000
.1250
.1250
DRILL THRU FOR
#6 CLEAR 5 PLCS.
.5000
3.8000
7.1000
7.6000
1/1
DECOUPLER PLATE
DR/DSGN: D.L.
LEHIGH U. 8/84
FULL SCALE: INCHES
TOL. +- .010
UNLESS SPECIFIED
PROPRIETARY INFORMATION OF LEHIGH UNIVERSITY

figure 21



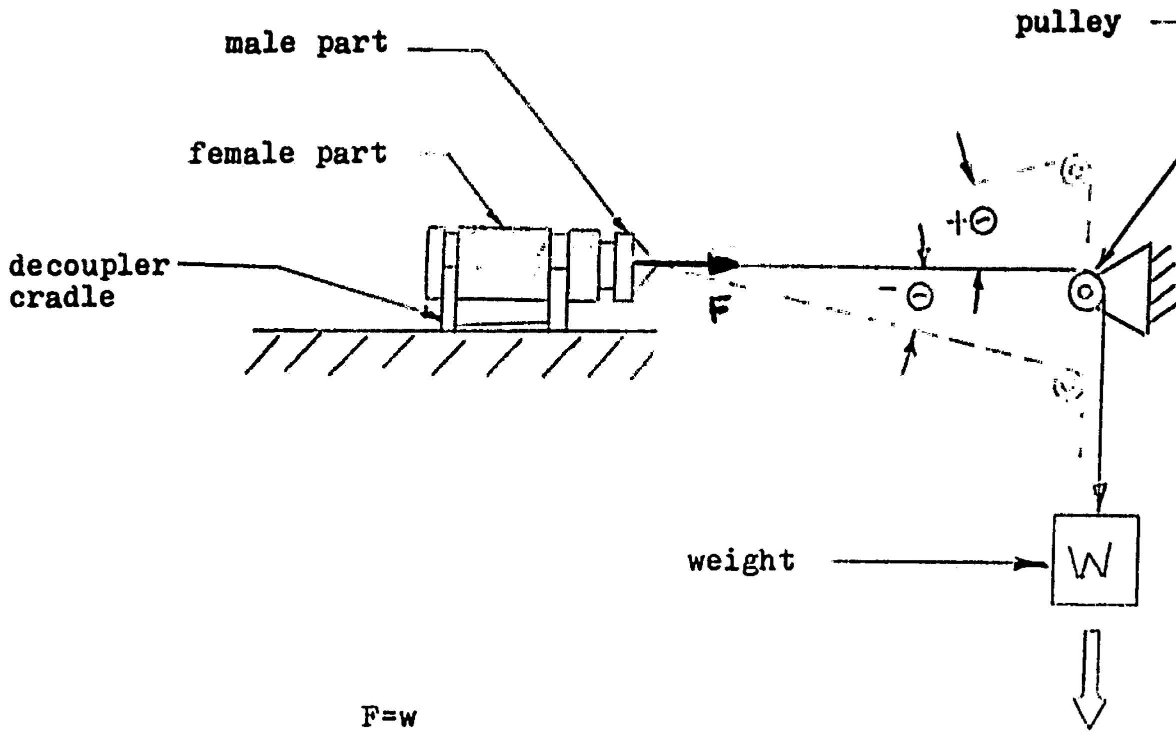

ball detent locked

figure 22




spring plunger locked with release pin inserted

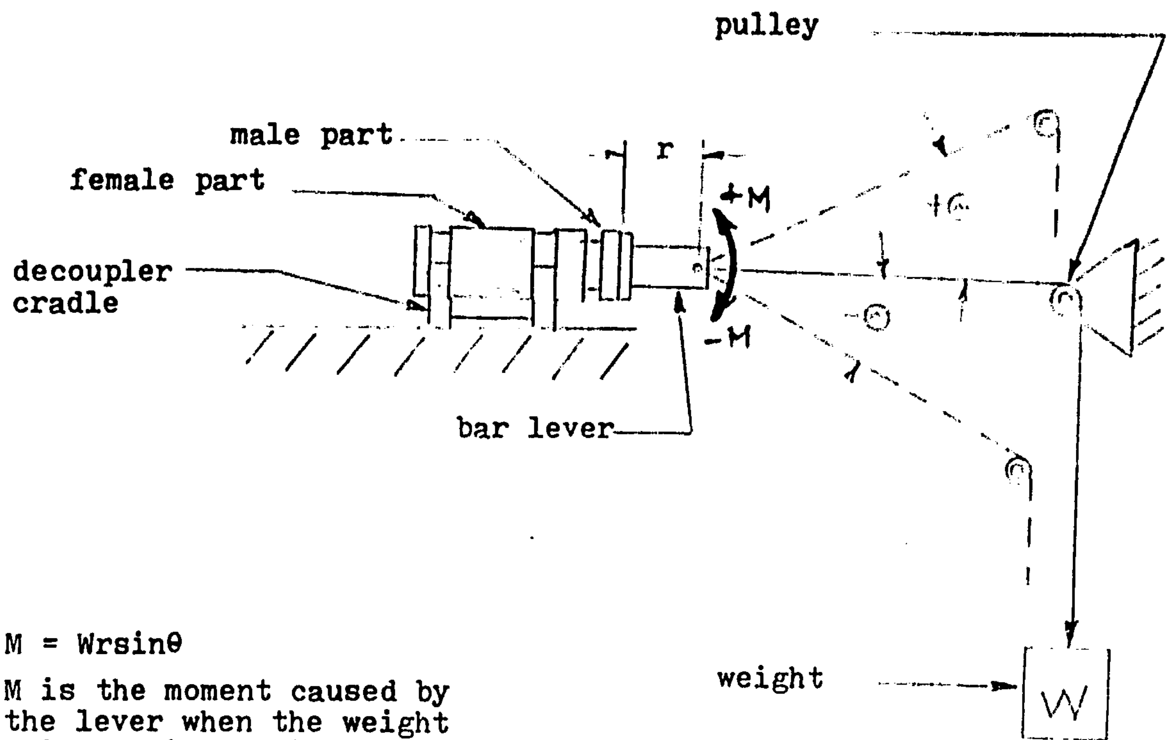
figure 23




Force Test
figure 24

F=w

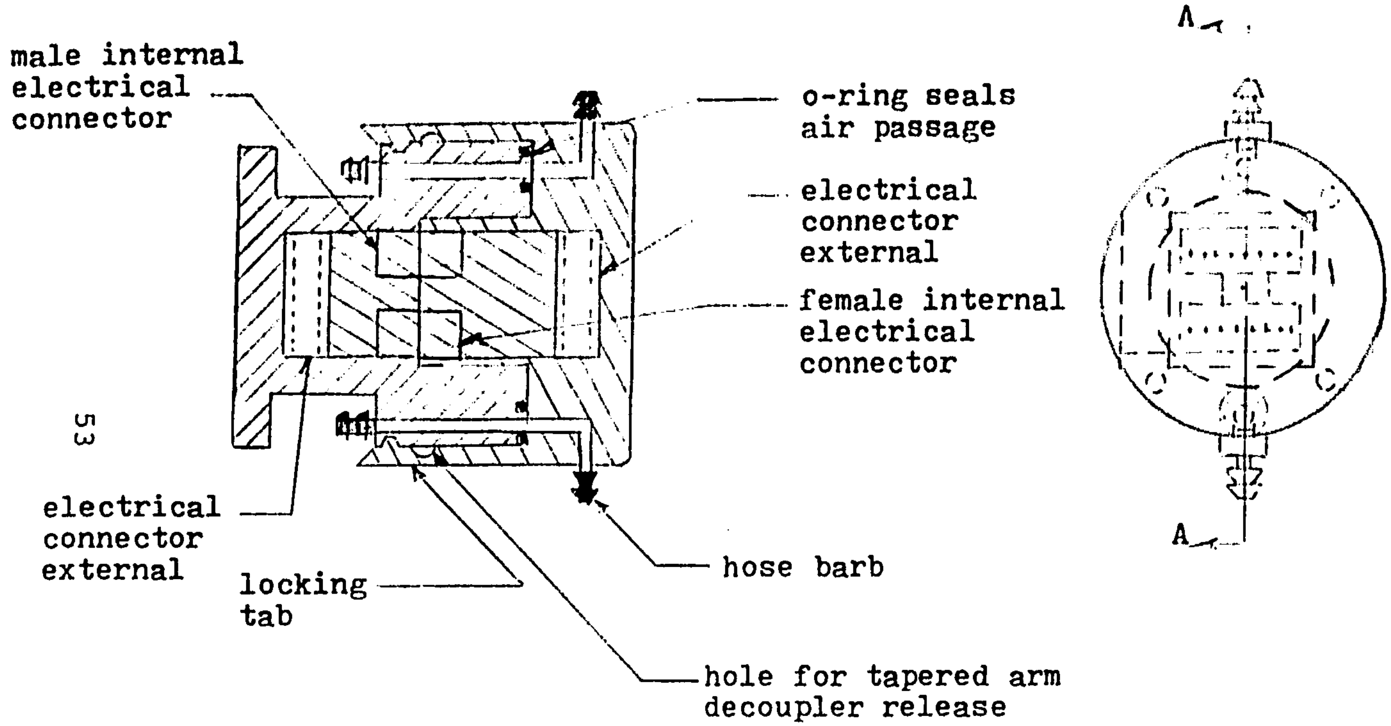
F is the force required to release the male part
w is the weight which is increased until release




$M = Wr\sin\theta$

M is the moment caused by the lever when the weight W is applied, r is the lever length, θ the angle of inclination above the neutral axis (or the axis axial to the male part)

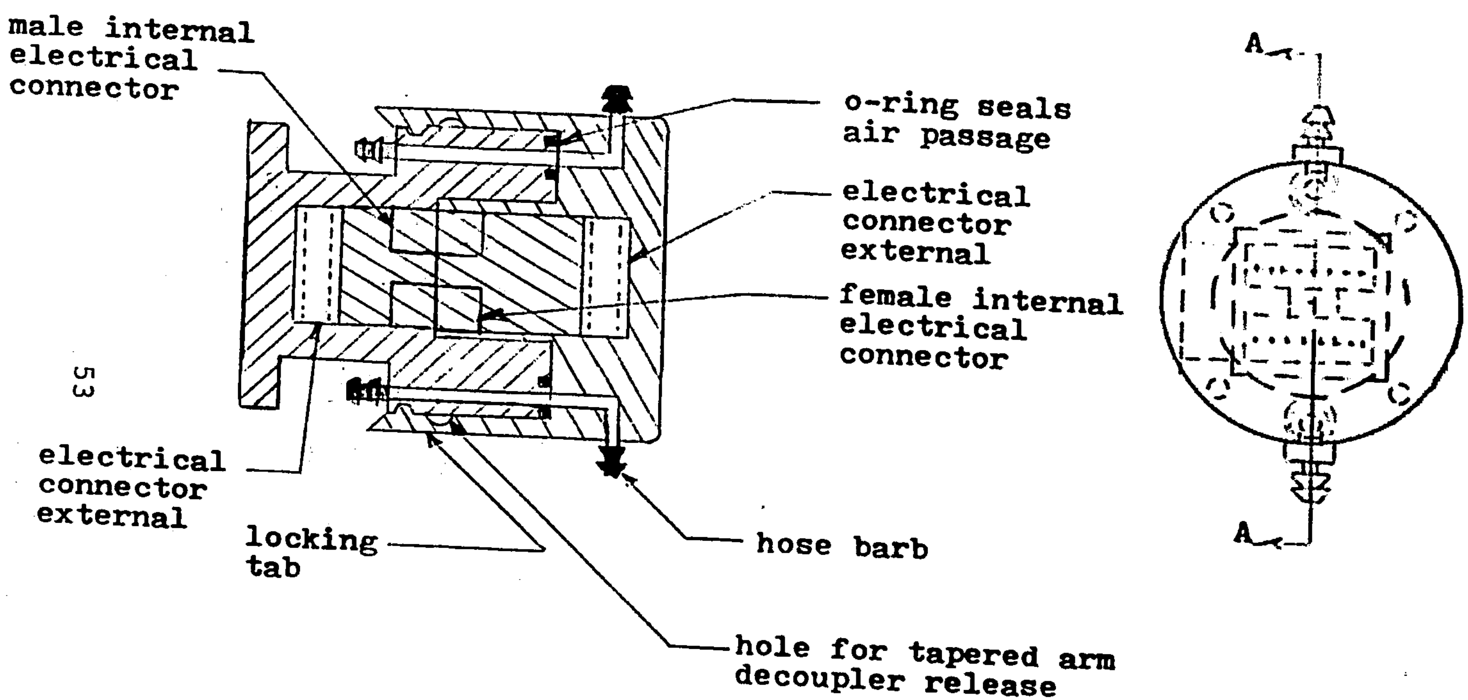
Moment Test
figure 25




section A-A

Note: see connector detail on figure

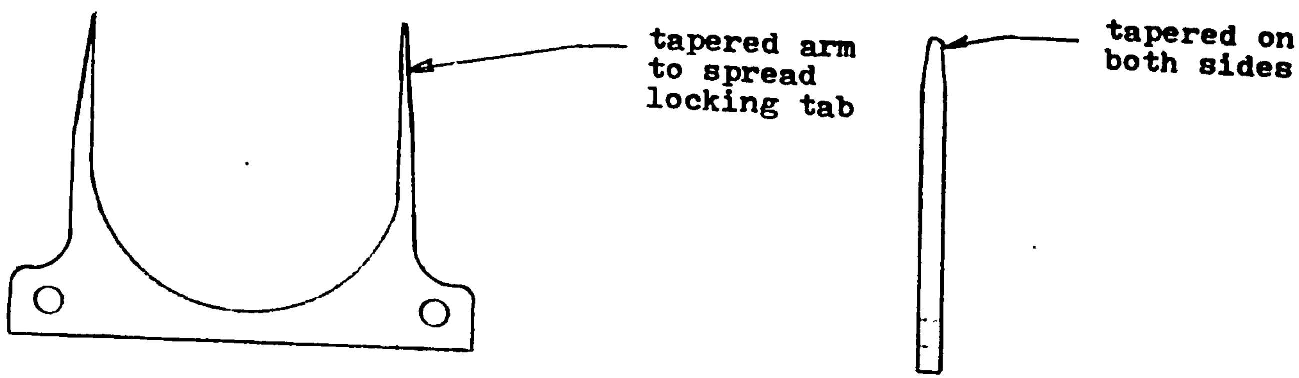
Conceptual Injection Molded Design
figure 26




section A-A

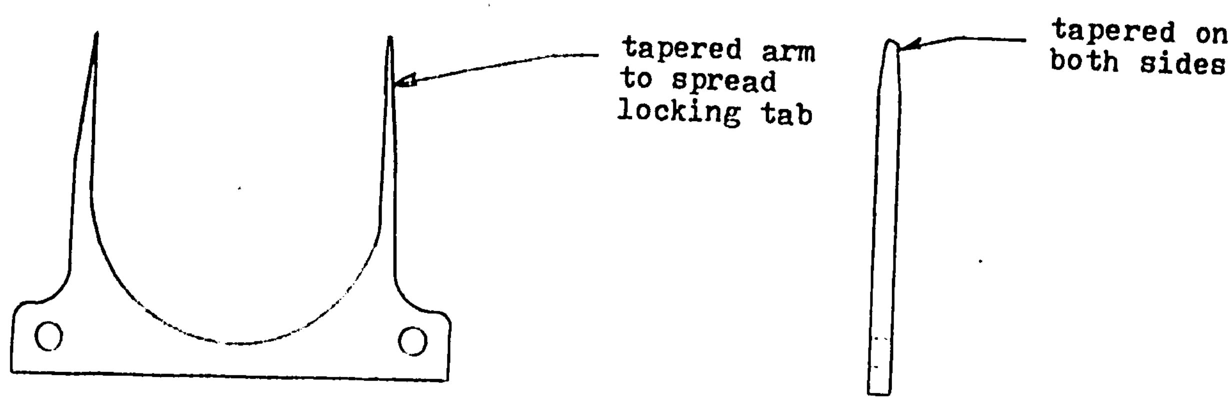
Note: see connector detail on figure

Conceptual Injection Molded Design
figure 26



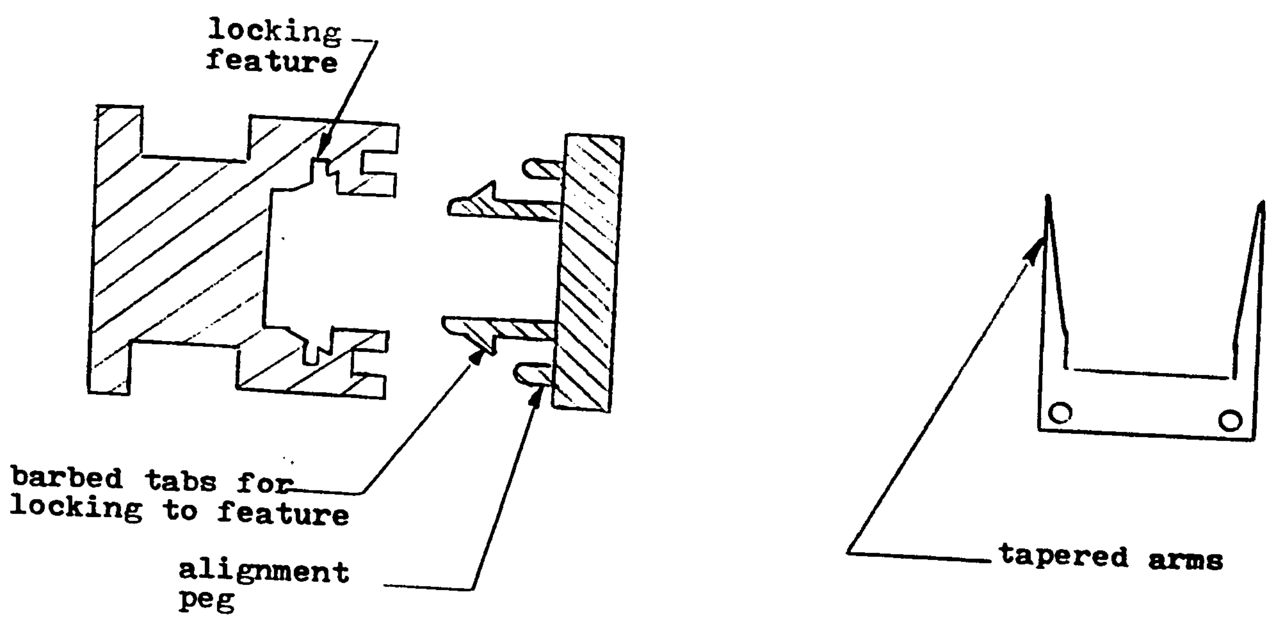

Decoupler
figure 27

Note: decoupler for use with injection molded concept. construct of steel




Note: decoupler for use with injection molded concept. construct of steel

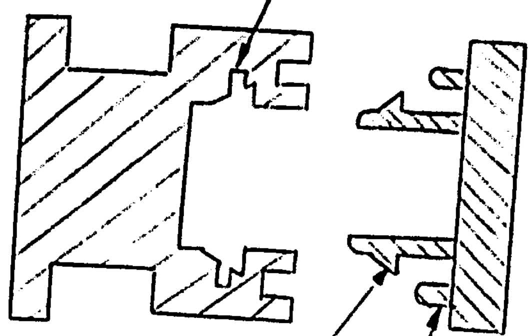
Decoupler
figure 27



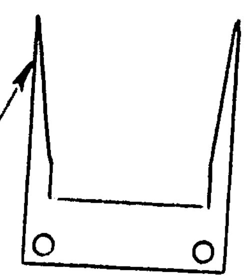

Internal Locking Concept
(not detailed)

Decoupler

Internal Locking for Injection Molded Part
figure 28

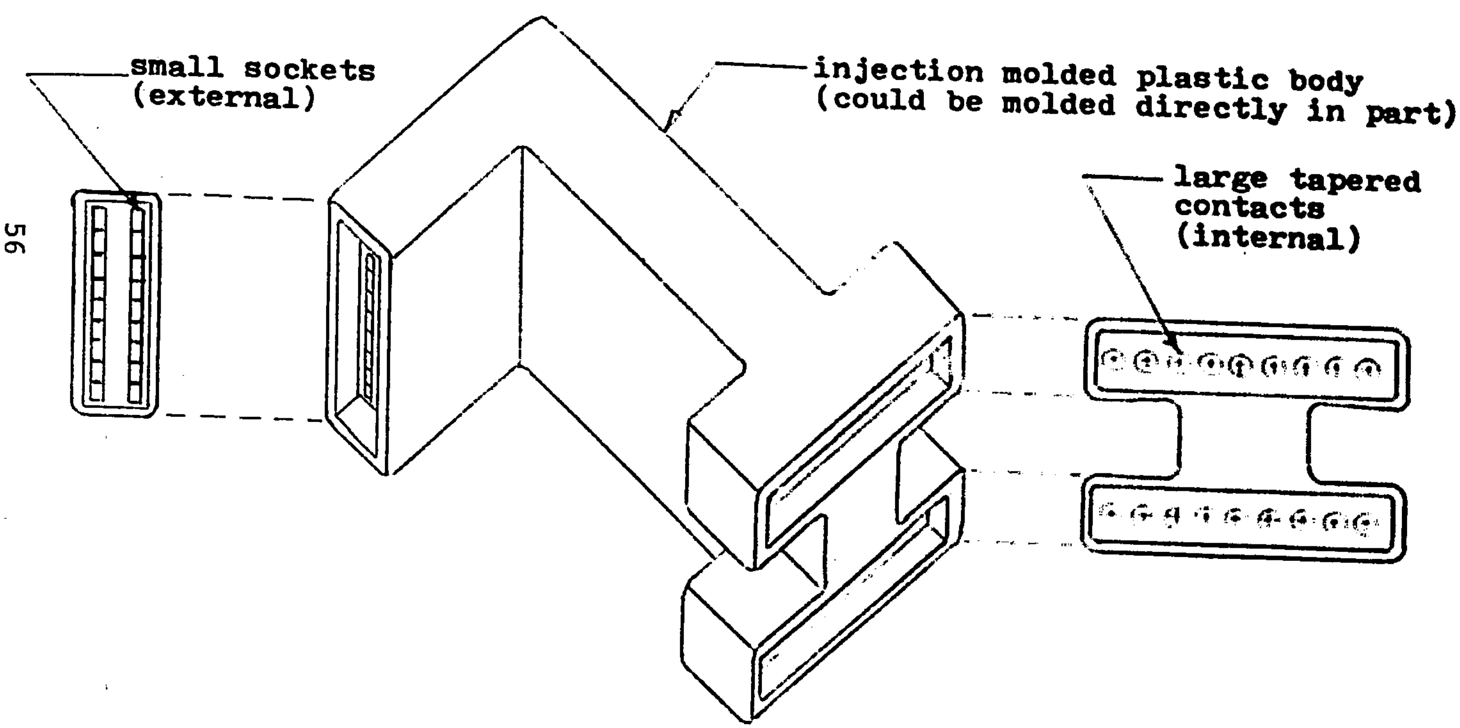



Internal Locking Concept
(not detailed)

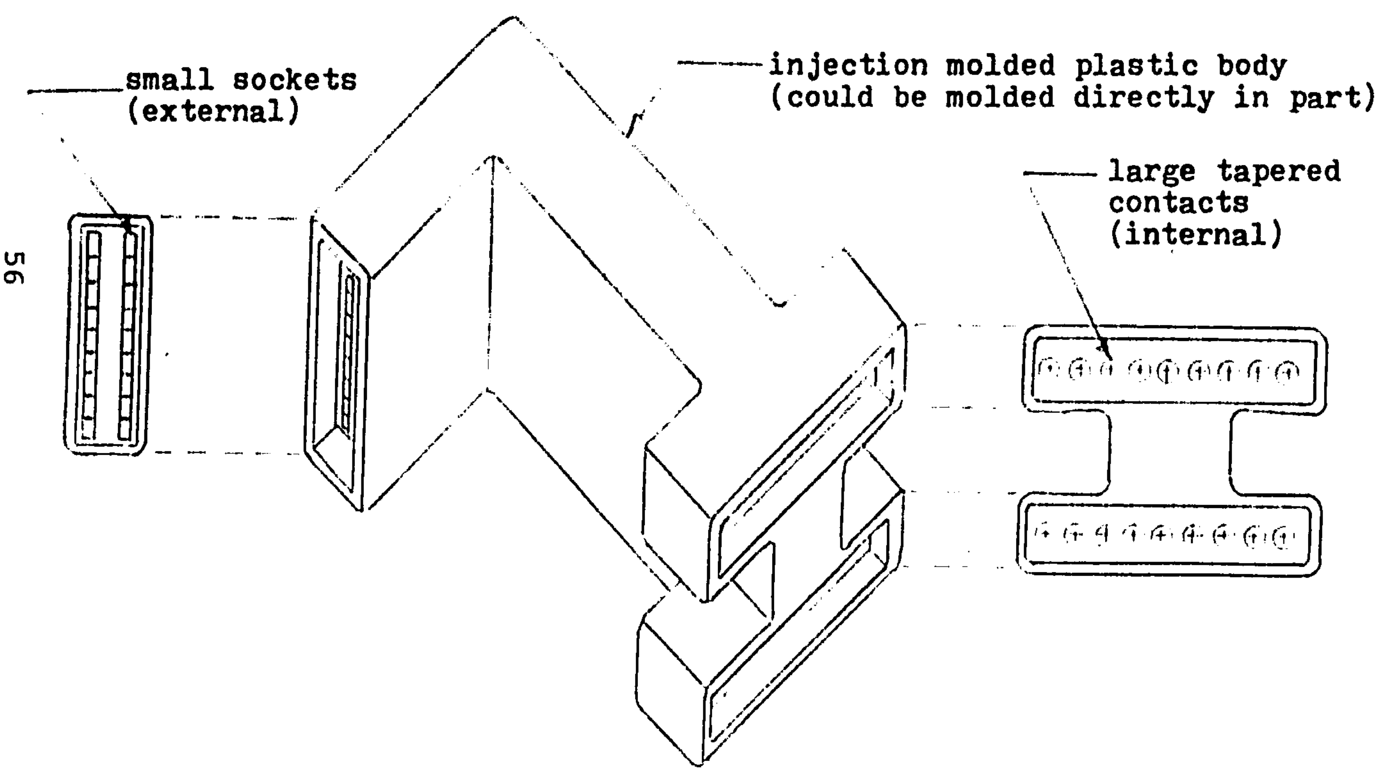



Decoupler

Internal Locking for
Injection Molded Part
figure 28

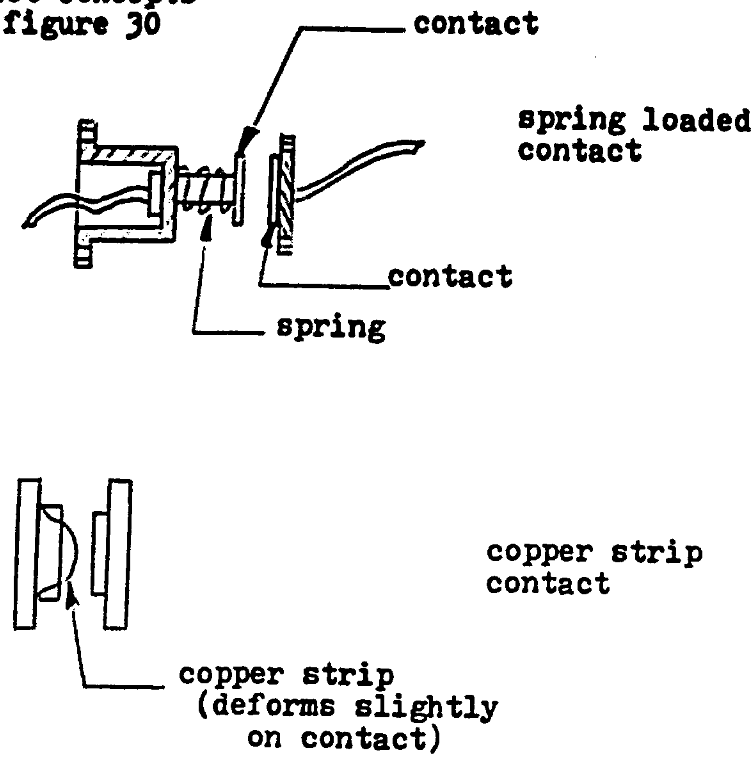


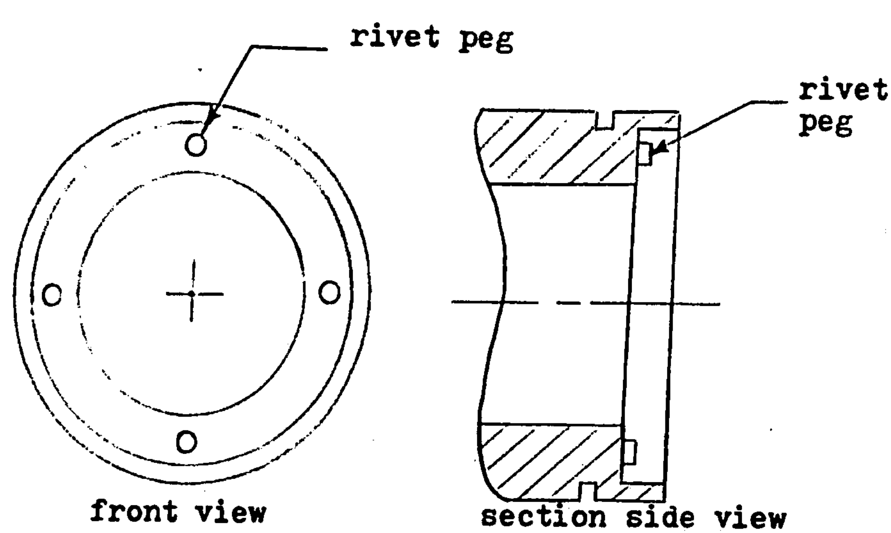

Connector Detail
figure 29



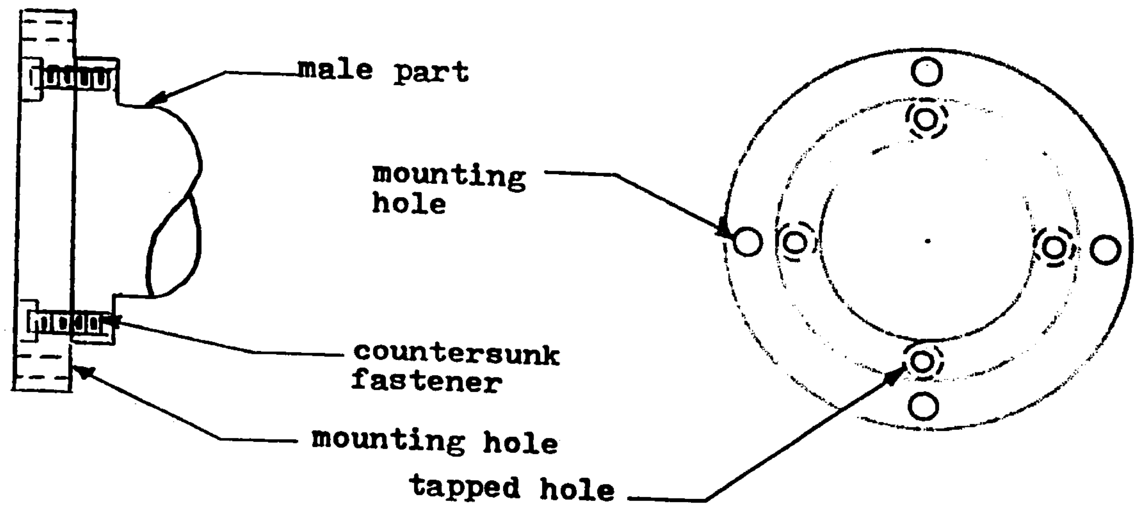

Connector Detail
figure 29

**Contact Concepts**
**figure 30**



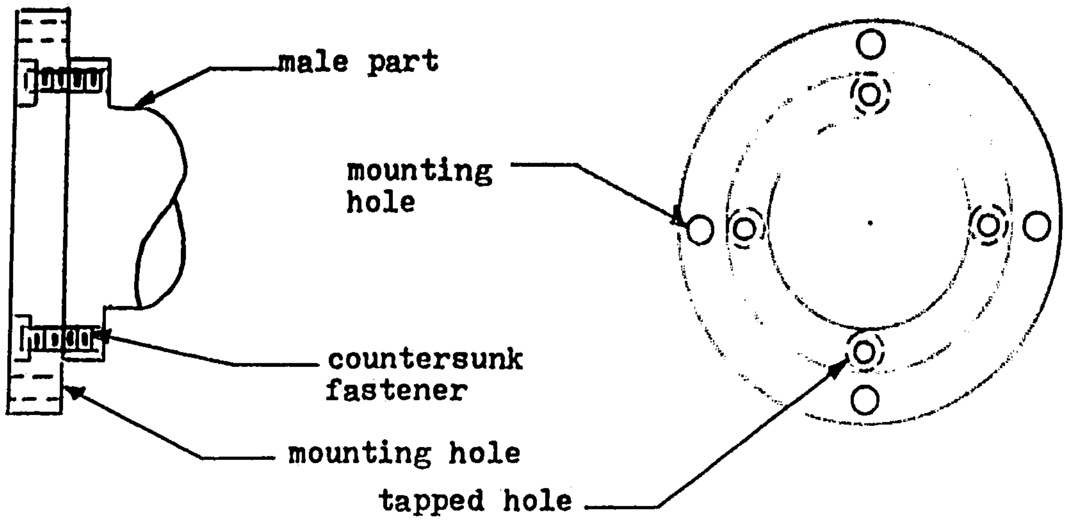




Integral Rivets
figure 31



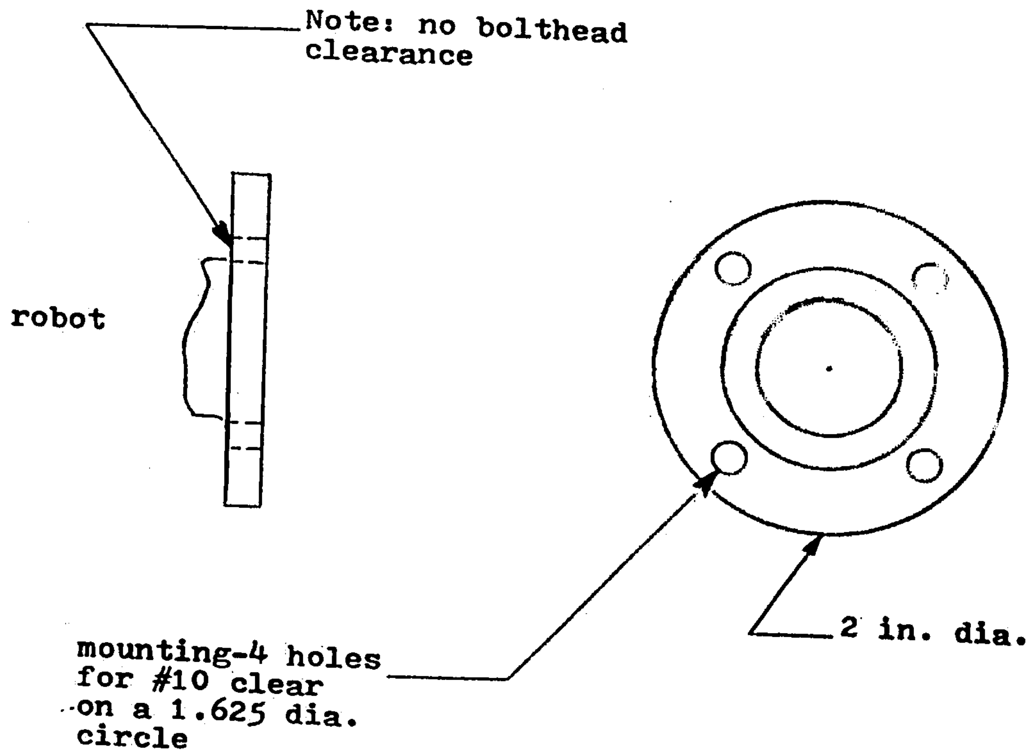

Note: plate is bolted to male part and then the whole assembly is bolted to a larger robot wrist flange

Adapter Plate
figure 32

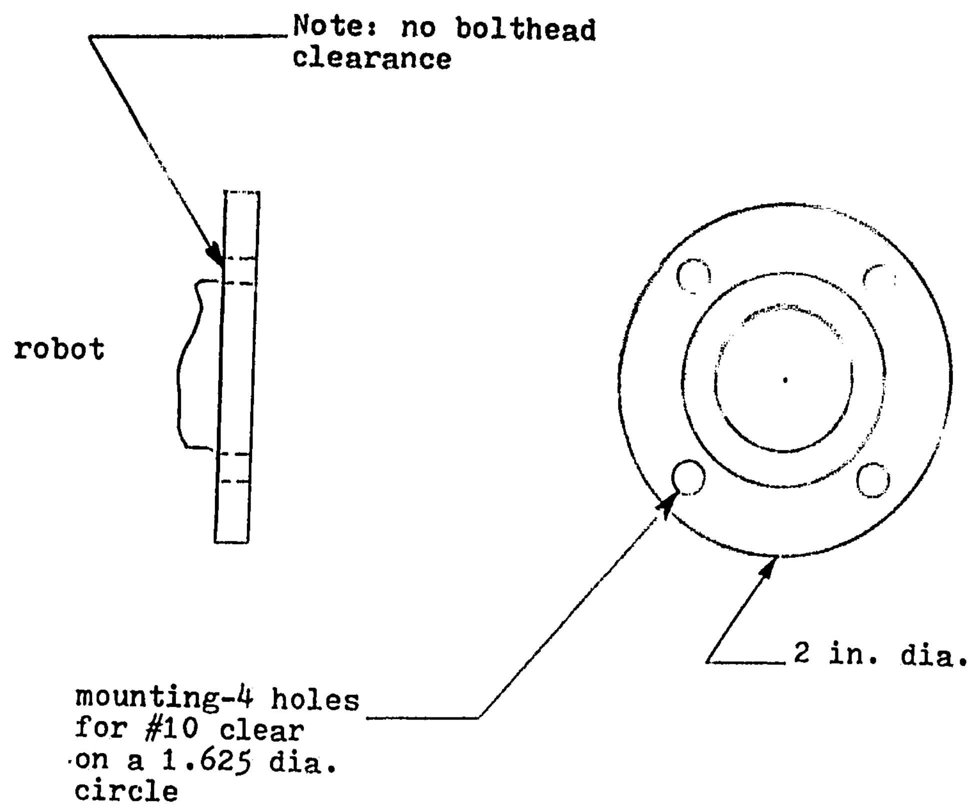



Note: plate is bolted to male part and then the whole assembly is bolted to a larger robot wrist flange

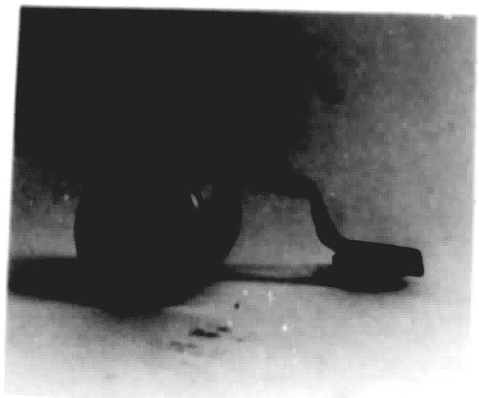
Adapter Plate
figure 32




Wrist Flange of Puma 560.
figure 33



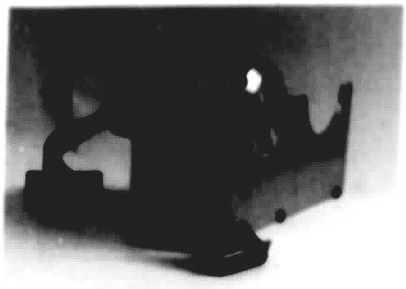

Wrist Flange of Puma 560, figure 33



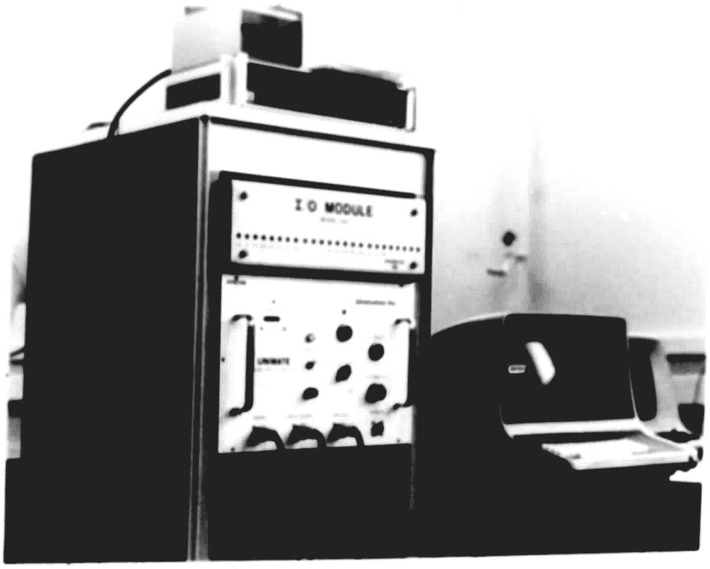
end effector mount
(female part)

wrist mount
(male part)

decoupler
(note pin that
compresses
spring plunger)

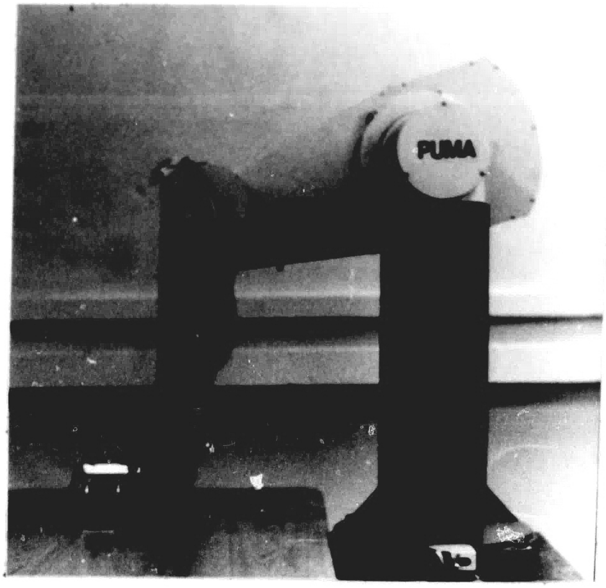


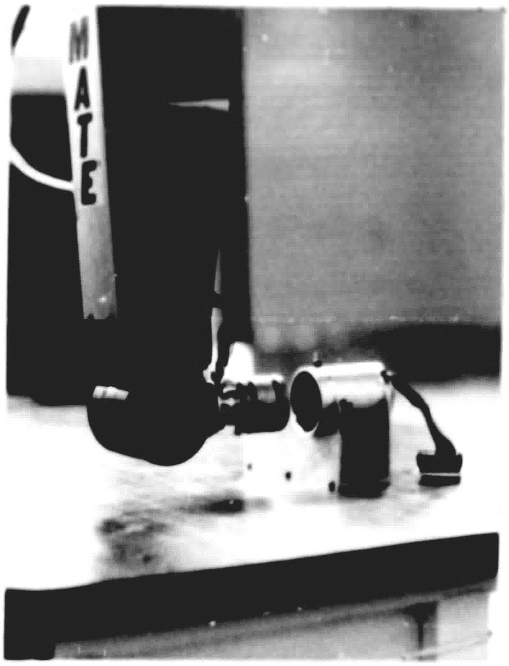
complete part on
decoupler




Puma 560
controller
&
terminal

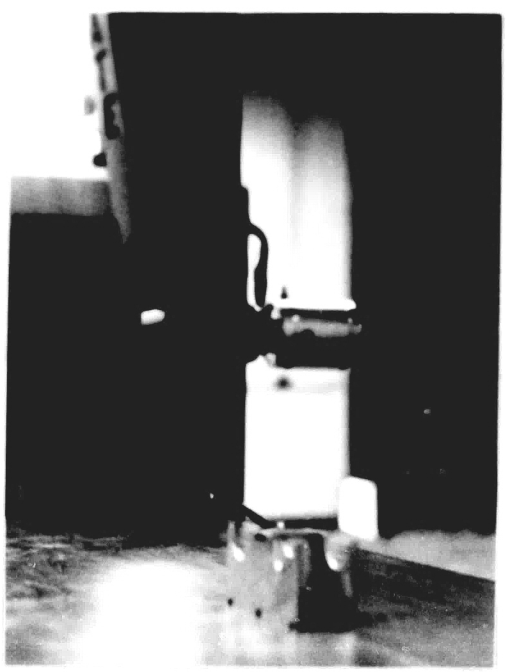
side view of
part mounted
on robot and
in decoupler






←(1)

(2)↑



←(3)

Note: no end effector present (for clarity)

sequence of photographs show :
1) coupling before insertion
2) inserted and locked
3) out of decoupler ready for work

pneumatic gripper with tactile sensing
mounted to end effector interchange device,
picture shows pneumatic and electrical
connections between the robot and the
interchange device, as well as connections
from the device to the end effector

## Appendix - Error Analysis and Results for the Force and Moment Test

Error Analysis:

Sources of error and tolerance (+/-):

dW1 = measure of release force = 2.0 oz

dW2 = accuracy of known weight = 0.1 oz

dW3 = accuracy in measure of the cable and weight holder and pulley friction = 1.0 oz

dΘ1 = angular inaccuracy in determining if neutral axis was level with respect to the male part = .25 deg.

dΘ2 = in accuracy in reading theta, the angle of inclination, with respect to the neutral axis = 0.5 deg.

dr = inaccuracy in measuring the moment arm length = .125 in.

Results:

Force Test:

average force to release Θ = 0.0 deg. = 6.68 +/- .14 lbs.

angles when jamming occurs: Θ = -11.5 +/- .56 deg.
= +13.5 +/- .56 deg.

maximum force to release just before critical angle = 7.42 +/- .14 lbs.

Moment Test:

angles where jamming occurs: Θ = +13.0 +/- .56 deg.
- 2.0 +/- .56 deg.

moments at jamming angles = +4.21 +/- .278 in.-lb.
-.652 +/- .185 in.-lb.

Using a statistical average for overall error calculation

we find for: $F = W$ ; $M = Wr \sin\theta$ — refer to figures 24 and 25 for test description

$r$ = moment arm length = 2.75 in

$\sin\theta$ = sin of inclination angle $\theta$

$W$ = weight applied

$F$ = force to release male part

$M$ = moment applied vertically to male part (see figure 25)

Error in $\theta$

$$\frac{d\theta}{\theta} = \sqrt{\left(\frac{d\theta 1}{\theta}\right)^2 + \left(\frac{d\theta 2}{\theta}\right)^2}$$

divide by $\theta$

$$d\theta = \sqrt{(d\theta 1)^2 + (d\theta 2)^2}$$

= calculated total error in $\theta$

Error in F

$$\frac{dF}{F} = \frac{dW}{W} = \sqrt{\left(\frac{dW1}{W}\right)^2 + \left(\frac{dW2}{W}\right)^2 + \left(\frac{dW3}{W}\right)^2}$$

divide by W

$$dF = dW = \sqrt{(dW1)^2 + (dW2)^2 + (dW3)^2} =$$

calculated total error in F

Error in M

$$\frac{dM}{M} = \sqrt{\left(\frac{dr}{r}\right)^2 + \left(\frac{dW1}{W}\right)^2 + \left(\frac{dW2}{W}\right)^2 + \left(\frac{dW3}{W}\right)^2 + \left(\frac{\mathrm{Sin}d\theta 1}{\mathrm{Sin}\theta}\right)^2 + \left(\frac{\mathrm{Sin}d\theta 2}{\mathrm{Sin}\theta}\right)^2}$$

Knowing dW reduce to:

$$\frac{dM}{M} = \sqrt{\left(\frac{dr}{r}\right)^2 + \left(\frac{dW}{w}\right)^2 + \left(\frac{\text{Sin}^2 d\theta 1 + \text{Sin}^2 d\theta 2}{\text{Sin}^2 \theta}\right)}$$

dW and dθ values:

$$d\theta = \sqrt{(.25)^2 + (.5)^2} = \underline{.56 \text{ degrees}}$$

$$dF = dW = \sqrt{(2)^2 + (.1)^2 + (1)^2} = \underline{2.24 \text{ ounces}}$$

$$= \underline{.140 \text{ pound}}$$

dM sample calculation:

$$\frac{dM}{(6.8)(2.75)\text{Sin}(13)} = \sqrt{\left(\frac{.125}{2.75}\right)^2 + \left(\frac{.140}{6.8}\right)^2 + \left(\frac{\text{Sin}^2(.25)+\text{Sin}^2(.5)}{\text{Sin}^2(13)}\right)}$$

For W = 6.8 lb. r = 2.75 in. θ = 13 deg. M = WrSinθ

dM = .278 in lb

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